VISION

To be a leading research institute for innovative energy solutions.

MISSION

To be a centre-of-excellence for advanced research, development, and demonstration of innovative energy solutions with global impact by:

• Advanced research enhancing the efficiency of energy systems while maximizing the synergies of alternative energy sources
• Enabling knowledge creation and technology transfer by engaging with government agencies, research institutions and industries
• Creating a multidisciplinary and collaborative environment for the delivery of energy solutions and national sustainability goals
In the coming decades, in order to sustain life and standards of living, which we have grown accustomed to, we must develop solutions for massive scaling of affordable sustainability solutions, develop means to reduce our greenhouse gas (GHG) emissions, and address UN’s sustainable development goals.
DIRECTOR’S MESSAGE

The global challenge that we face today is climate change. The basic issue with climate change is GHG emissions; and the key opportunities of reducing emissions are through energy efficiency and through implementation of sustainable, low-carbon fuels. Clean electricity can come from solar panels, from hydrogen, from integration of wind and from other renewables.

Singapore has set forth to develop cost-competitive energy solutions to improve its energy efficiency, reduce its carbon emissions, broaden its energy options while addressing both national sustainability goals and opportunities for green growth. Cities account for 75% of energy use and 80% of the CO2, and thus Singapore offers a unique living-lab environment to develop, implement, and eventually export sustainability solutions to other megacities around the world.

ERI@N focuses its efforts entirely on means of reducing energy intensity and finding new ways of sustainable electricity generation. The ERI@N mission manifests itself into a comprehensive effort on electricity generation & storage, grid systems, and urban solutions in a living lab environment. Besides the Interdisciplinary Research Programmes (IRP) that address each of these domains, the two Flagship Programmes, EcoCampus and Renewable Energy Integration Demonstrator - Singapore (REIDS) focus on bold and significant outcomes in rational energy end use and renewables integration.

Integral part of these efforts to deliver innovative energy solutions is the pan-university nature of ERI@N that consolidates energy research and promotes multidisciplinary collaboration across colleges of engineering, science, business, humanities, arts and social sciences. Key partnerships with global research and technology leaders in both academia and industry are also essential towards delivering our mission.

The Institute distinguishes itself through excellence in basic research directed towards outcomes of high industry relevance, with focus on systems-level research and integration for tropical megacities.

“ERI@N focuses its efforts entirely on means of reducing energy intensity and finding new ways of sustainable electricity generation.”
Sustainability challenges, albeit an unparalleled threat to business-as-usual, also represent a remarkable opportunity for research, innovation and green growth.

While Singapore depends mainly on imported oil and gas to meet its energy demand, and is acknowledged as being an alternative-energy disadvantaged economy, Singapore has set the target of stopping any increase to its greenhouse gas emissions by 2030. It also pledged to reduce its energy intensity by 36 per cent from 2005 levels by 2030 by pursuing energy efficiency in both industrial and residential sectors, improving public transport, and increasing renewable energy deployment.

To support these sustainability and economic growth goals, the Nanyang Technological University (NTU) has created the Sustainable Earth Office (SEO), as an initiative to coordinate the university’s efforts in sustainability, pushing frontiers of knowledge to support and build a prosperous and sustainable future for NTU, Singapore and the world.

The Energy Research Institute @ NTU (ERI@N) was established in 2010 under the SEO, aiming to develop and implement real-size demonstration projects, integrating the outcomes of its research initiatives to apprise the public and private sectors as to the in-the-field application of innovative energy transition technologies. The Institute integrates research across NTU as a whole in the context of the energy challenge, and then helps translate outcomes into industry and practice.

ERI@N works closely with Singapore public agencies such as National Research Foundation (NRF), Economic Development Board (EDB), Energy Market Authority (EMA), Building Construction Authority (BCA), and private sector entities in support of on-going energy transitions, while also remaining sensitive to the diverse needs of South East Asia. It does so in close collaboration with both local and global industrial partners as well as with world-leading academic institutions.

The Interdisciplinary Research Programmes (IRPs) at ERI@N focus on applied research at Technology Readiness Levels (TRLs) 1-6, while the Flagship Programmes focus on higher TRLs of 4-7. To bring successful RD&D solutions to the market, the ERI@N Accelerator Programme (EAP) nurtures and supports start-ups or spin-off companies that can take up commercial aspects at TRLs 6-8. The two Flagship programs, viz. EcoCampus and Renewable Energy Integration Demonstrator Singapore (REIDS) can be looked upon as culmination of applied research carried out in various IRPs towards life-scale and demonstrable solutions.

EcoCampus focuses on energy efficiency and urban sustainability and would rely on applied research related IRPs such as Sustainable Building Technologies, Future mobility Solutions and Renewable Integration and microgrids. The REIDS’ flagship programme is focused on affordable energy access via renewable energy integration for island communities and would encompass solutions developed in the Renewable and Low Carbon Generation IRP, as well as Fuel cells and Energy Storage programmes.

The start-ups supported under the ERI@N Accelerator Programme (EAP) also benefit from the deep technological expertise of the IRPs, as well as the opportunities for demonstration and test bedding offered by the Flagship Programmes. The EAP also helps ERI@N address market gaps that may not be fully covered by the industry partners, especially given the technological niche and early stage of development that the start-ups focus on.

Thus, the three structural programmes of ERI@N go hand-in-hand synergistically to offer innovative energy solutions that are technologically sound, developed up to life-scale demonstration through RD&D and are market ready.
EXECUTIVE COMMITTEE

Prof Subodh Mhaisalkar  
ERI@N Executive Director  
Professor Mhaisalkar is a faculty member in the School of Materials Science and Engineering, and his areas of expertise include nanomaterials, thin film photovoltaics, and printable electronics and charge storage.

Prof Choo Fook Hoong  
ERI@N Co-Director  
Professor Choo’s areas of expertise are Energy Management, Data Analytics and MVAC Systems, LDAC Air-conditioning System, Power Electronics and Drives, EVS and Electromobility, Smart Grids - Hybrid DC/AC Grids and Renewable Energy Systems (Solar PV and Thermal).

Prof Hans B (Teddy) Püttgen  
ERI@N Senior Director  
Prof Püttgen is a professor in the School of Electrical and Electronics Engineering, and his expertise includes Energy Systems, Renewables Integration, and Power Engineering.

Prof Chan Siew Hwa  
ERI@N Co-Director  
Professor Chan is a faculty member in the School of Mechanical and Aerospace Engineering, and his areas of expertise include fuel cells, fuel reforming and internal combustion engines.

Prof Yoon Soon Fatt  
ERI@N Executive Director  
Professor Yoon is Chair of the School of Electrical and Electronic Engineering at Nanyang Technological University (NTU) Singapore, where he is Professor of solid-state electronics and photonics.
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STAFF BY COUNTRY

 Americas
 1% PhD

 Europe
 10% Bachelor

 Asia
 88% Masters

 Oceania
 1% Americas

 Staff by Country:

- **Asia**: 79% China, 67% India, 28% Singapore, 12% Malaysia, 9% Indonesia, 4% Myanmar
- **Americas**: 1% Brazil, 1% Canada
- **Europe**: 4% France, 3% Italy, 2% UK, 1% Poland, 1% Sweden, 1% Switzerland
- **Oceania**: 2% Australia

Annual Report 2015-2016
The Interdisciplinary Research Programmes (IRPs) are at the core of ERI@N’s applied research focus. They cover relevant technological domains to Singapore’s sustainability goals.

ERI@N creates immense opportunities for technoeconomic growth in the region. Such efforts position Singapore as world leader provider of sustainable and energy efficient solutions for the developing world.

The IRPs can be broadly categorised to focus on critical aspects of sustainable energy development, viz. energy systems, grid systems and urban solutions. The focus of each IRP is to develop innovative and cost-effective solutions to address the sustainable energy challenges, such as energy efficiency and low carbon alternative energy systems.

Although the IRPs are organised as separate groups to provide sufficient research depth, there are several overlaps and common technological bases such as advanced materials, modelling and simulation capabilities, control techniques, and reliability science.
Interdisciplinary Research Programmes
Solar energy is the most abundant renewable energy source; its harvesting on a global scale shows the potential to fulfill the world’s energy demand. Photovoltaic (PV) devices have great potential as renewable energy sources, yet uptake is challenged by upfront capital costs and the (currently) low petroleum prices. To become competitive with fossil fuels, it is necessary to reduce the total cost of solar energy, by e.g. reducing the cost of the photovoltaic cells or by increasing their power conversion efficiencies. The photovoltaic market is currently dominated by crystalline Si solar cells with best module efficiencies in the range of 20%.

At ERI@N the focus is on non-silicon technologies such as CIGS and halide perovskite materials for cost-effective solar energy conversion, with a sister institute (SERIS) focusing on Si technologies. The key rationale to these research efforts is to employ low-energy intensive manufacturing processes, in which cost-effective and abundant starting materials are predominantly deposited via solution-processing techniques – thereby avoiding energetically expensive vacuum processes (i.e. low energy payback time). Additionally, the employed fabrication techniques should allow for scale up towards large area energy harvesting devices into industry and practice.

Programme at a glance

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Thrust 1: Hybrid halide based perovskite for photovoltaics

Hybrid halide perovskites combine the solution processability required for facile manufacturing with high efficiencies required for reduced levelised cost of electricity. The group at ERI@N has been very active in the area of perovskite solar cells. The core-strength of the group is the development of a large variety of novel perovskites. This new materials development is coupled with fundamental photophysical characterisation necessary to understand the utility of these materials for energy harvesting applications. The breadth of the activities in the group involves the development of new device concepts and interfacial layers that enable advantages such as mechanical flexibility, compatibility with building integrated architectures and facile manufacturability. Challenges for perovskite solar cells include toxicity and stability. These have been tackled through the development of tin, germanium and antimony based alternatives. Intrinsic stability can be modulated in multi-dimensional perovskites by incorporation of hydrophobic cations or through the utilisation of organic cations with low volatility. In parallel to these fundamental activities, two specific tasks with more advanced technology readiness levels are also being pursued. The first involves the development of tandem solar cells which involves the fabrication of perovskite solar cells on existing solar cell technologies (e.g. Si). The second project involves the scaling up of perovskite solar cells to a larger area. Utilising printing processes, perovskite solar cells with an active area of 70 cm² have been fabricated with impressive efficiency (~11%).

Thrust 2: Thin film chalcogenide photovoltaics

Chalcogenide solar cells [including Cu(In,Ga)Se₂, Cu(In,Ga)(S,Se)₂, CuIn(S,Se)₂, and CuZnSn(S,Se)₂] are of interest due to their high absorption coefficient and suitable bandgap for solar absorption. The group at ERI@N focusses on solution processing these films utilising aqueous methods. These solar cells have been consequently scaled up to active areas of at least 25 cm². Doping into CuZnSnS₂ to improve device open circuit voltage and power conversion efficiency is also being pursued. Additional focuses include the utilisation of Cd-free buffer layers for efficient chalcogenide solar cells.

Thrust 3: Solar fuels

Utilising phot electrochemical processes to store solar energy within the chemical bonds of a fuel have been pursued for both hydrogen production as well as CO₂ to hydrocarbon conversion. A particular focus has been the development of oxide-based photoanodes and their utilisation in tandem with perovskite solar cells for unassisted water splitting. Additional topics of investigation include control of the CO₂ reduction products by modulating the surface adsorption properties of the catalysts.
Project 1: Studies in Lead Halide Perovskites

The group working in the area of lead halide perovskite solar cells at ERI@N has been active since 2013. Through a fundamental understanding of the long-range balanced charge transport in CH3NH3PbI3 perovskites [Science, 2013, 342, 344-347], the team has been able to develop other lead perovskite systems (e.g. FAPbI3) [JPCC, 2014, 118 (30), 16458-15462], colour management (i.e. band gap engineering), and novel device concepts (e.g. flexible nanowires or nanorods) [Nanoletters, 2013, 13 (6), 2412-2417], etc.

From ‘model systems’ (i.e. pristine thin films grown form physical vapour deposition or single crystals which enable precise tuning of the composition), a fundamental understanding of the materials’ system and their structural limitations could be derived. High efficiency photovoltaics (17.9% - Figure 1) have been achieved through processes which improve the morphology of the thin films including anti-solvent treatments. However, a clear understanding of the interplay of morphological effects from substrate/perovskite anti-solvent treatment on the charge dynamics is currently lacking. Through detailed ultrafast optical spectroscopy and scanning electron microscopy, we were able to correlate the morphology-kinetics relationship.

Our findings reveal that despite the significant surface morphology improvement, only a slight improvement in the carrier relaxation lifetimes was observed – attributed to the competition between the morphology improvements and the increased surface traps densities [PCCP, 2016, DOI: 10.1039/ C6CP02640K].

1. Tandem perovskite solar cells: currently, single junction Si cell efficiencies are close to the Shockley-Queisser (SQ) limit of 33% and major performance advances have ground to a halt, with maximum efficiencies stagnating at 25% since 2009. The SQ limit can be exceeded through the recovery of thermalisation energy, by employing layers with different band gaps to absorb the solar spectrum, thus reducing the mismatch between material band gap and incoming photon energy. In theory, PCE greater than 40% can be attained with two-layer Perovskite-Si tandem cells, with proper band-gap selection. The most facile implementation is the 4-terminal tandem where the two cells are stacked (but are electrically isolated). Although there are no requirements on the interfacial layer, nor a voltage or current match, the subsequent balance of systems (BOS) is doubled, which potentially increases the overall costs. An overall PCE of 17.66% was attained with a stacked perovskite-CIGS solar cell configuration, higher than the individual solar cells [manuscript in preparation].

The second configuration, a 2-terminal monolithic tandem configuration connects both devices in series which produces a higher voltage at the terminals, but concurrently imposes the restriction that current flowing through both devices should be equal. This entails careful selection of each layer’s band gap and film thickness in order to control the absorption and hence current flow in each layer. The 2-terminal system requires only one set of BOS but is sensitive to illumination intensity and spectral component variations. A tandem efficiency of 10.21% was obtained. Selection of the recombination layer and good control of the interface were found to be critical in obtaining high efficiencies.

2. Other major accomplishments: include the first demonstration [Nature Materials, 2014, 13, 476-480] of amplified spontaneous emission (ASE) from solution-processed organic-inorganic (CH3NH3PbX3 where X = Cl, Br, I with visible spectral tunability from 390-790 nm) at strikingly low thresholds (12 µJ cm-2). The low ASE thresholds stem from their large absorption coefficients and low Auger recombination. Other first reports include the first solution-processed all-inorganic CsPbBr3 LED [JPCL, 2015, 6, 4360-4364] and the formation of CH3NH3PbBr3-(OA)2PbBr4 (perovskite-perovskite) core-shell nanoparticles of increased stability (> 2months) and near-unity photoluminescence quantum yield [Chem. Commun., 2016, 52, 7118-7121].

![Efficiency>17.9%](image)

Figure 1 High Efficiency Photovoltaics

<table>
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<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
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<tr>
<td>1.1</td>
<td>21</td>
<td>77.8</td>
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Our findings reveal that despite the significant surface morphology improvement, only a slight improvement in the carrier relaxation lifetimes was observed – attributed to the competition between the morphology improvements and the increased surface traps densities [PCCP, 2016, DOI: 10.1039/ C6CP02640K].
Project 2: Multidimensional and Lead-free Perovskites

In the past few years, perovskite PVs have shown unprecedented rapid advancement and the PCEs have exceeded 22% via optimizing the interlayers and device configuration. To allow the perovskite PVs to be commercialised, their ambient instability and toxicity need to be addressed. Thus, ERI@N has focused on developing lead-free perovskites and multidimensional perovskites which have intrinsic ambient stability.

1. Lead-free perovskites: A candidate for effective Pb-replacement is Sn, forming a +2 oxidation state, which is required to adopt the octahedral coordination in the perovskite structure. However, two main drawbacks have prevented the development of effective Sn-based perovskites for photovoltaic applications: (i) the low band gap and high conductivity generally presented for Sn-compounds and (ii) the instability of the Sn2+ which tends to form Sn4+. In addition to exploring additives to control the oxidation, research at ERI@N has focused on halide semiconducting systems where the Sn is in its most oxidised form. Four A2SnI6 (A = Cs+, Rb+, MA+ or FA+) perovskite materials have been synthesised by room-temperature solution-based process in ambient air. Except for Rb2SnI6, these compounds with cubic crystal structure are stable up to 150 °C. As for Rb2SnI6 with tetragonal crystal structure at room temperature, it possibly exhibits phase transition at around 50 °C and decomposes beyond 200 °C. Their bandgap values are correlated to A+ cation size (1.24, 1.30, 1.33 and 1.50 eV for Cs2SnI6, MA2SnI6, Rb2SnI6 and FA2SnI6, respectively) [Chem. Mater., 2016, manuscript in preparation]. Due to the wide variety of alternatives available as metallic replacement, a first-principle based screening strategy is essential, in which the focus is on high throughput computational screening that will initially search for candidate materials based on calculated bandgaps and thermodynamic stability. Experimentally, three AGeI3 (A=Cs, CH3NH3 or HC(NH2)2) halide perovskite materials were synthesised, shown to be stable up to 150 °C, and have bandgaps correlated to the A-site cation size [J. Mater. Chem. A, 2015, 3, 23829-23832]. Other systems that are under investigation include Cu, Sb and Bi based halide perovskite systems.

2. Multidimensional perovskites: The hygroscopic nature of perovskites, which arises since the inorganic layers are held together through electrostatic attraction between cationic and anionic species, allows water molecules to intercalate easily, and subsequently results in dissociation into ammonium salts and lead halide residues. Furthermore, vacancies in the perovskites will accommodate ionic migration and phase separation, which leads to compromised device performances under continuous illumination during full operation. The cationic and halide components in the perovskites can also be liberated by applying moderately high temperatures, causing thermal decomposition and deterioration in device performances. Multidimensional perovskites (Figure 2) have become promising candidates to surmount the challenges of ambient instability in conventional 3D perovskites. As compared to the pure 2D perovskites, multidimensional perovskites typically possess more ideal band gaps and better charge transport for PV applications. More importantly, the conductivity in the vertical direction (normal to the charge extraction layers in a conventional device configuration) can be higher in mixed multidimensional perovskites since the pure 2D perovskites tend to crystalize parallel to the substrate. We have employed nanostructuring of the perovskite to alleviate these challenges Nanostructured mixed-dimensional perovskites, (IC2H4NH3)2(CH3NH3)n-1PbnI3n+1 were applied in mesoscopic solar cells using a sequential deposition method under ambient conditions in which the dimensionality of perovskite is controlled by the dipping duration [Adv. Mater., 2016, 28, 3653-3661].
Project 3: Stability and Scalability of Perovskite Solar Cells

Stability of perovskite solar cells remains an area of focus in order to ensure that perovskite solar cells make the transition from a laboratory curiosity to a technological breakthrough. We have performed an initial study of long term stability at different temperatures (room temperature and 70 °C) under atmospheres for unsealed lead-iodide perovskite solar cells with thin and thick perovskite layer (capping layer) onto the mesoporous TiO2. At room T, solar cells in dry atmosphere (desiccator), N2 atmosphere and ambient atmosphere with thick perovskite capping layer were stable for more than 1000 h (degradation of efficiency <5%). In contrast, solar cells at 70ºC dramatically decreased the efficiency (~50% drop) in less than 400 h. We have also explored how surface defects could modulate efficiency and photoexcitation dynamics of organic-inorganic hybrid perovskite by comparing the photophysical phenomena in single crystals and thin films.

Two-photon-excitation techniques which have a much longer penetration depth (>102 μm) than conventional single photon excitation were utilised. Striking photophysical differences was found between the bulk and the surface parts. Excitation lifetimes were found to be significantly increased in the bulk. For MAPbBr3 single crystals, the surface trap density is estimated to be around 6.0 × 1017 cm-3, which is around two orders larger than that of the bulk (5.8 × 1015 cm-3). Correspondingly, the diffusion lengths of the surface excited species is ~130-160 nm, which is considerably reduced compared to the bulk value of ~2.6-4.3 μm. Recognizing that ambient stability is a critical factor, the device configurations chosen for scale up involved the use of mesoporous carbon which acted as an encapsulant while providing electrical connectivity.

1. Scaling of perovskite solar cells: The laboratory scale processes utilised in preparing perovskite solar cells which include multiple spin coating processes are not scalable for solar modules. Hence, the fabrication process was modified entirely into the fully-printable perovskite solar cells where the conventional spin coating method was replaced by screen-printing techniques. Additionally, the device architecture utilised included a mesoscopic hole collecting electrode which avoided the utilisation of vacuum based electrode evaporation. Additional advantages included (i) replacement of the Spiro-OMeTAD hole transport layer and Au cathode in the lab-scale process by a ZrO2 spacer layer and carbon cathode in the scaled-up process. (ii) Replacement of double step perovskite deposition in the lab-scale process by a single step perovskite deposition process (iii) all the spin coating steps in the lab-scale process are replaced by screen printing or drop casting techniques. With the screen printing capability, the perovskite solar modules are able to be scaled up to 70 cm2 active area (Figure 3). The large area cells showed a PCE ~11% with an excellent stability over 2000h in ambient conditions. The fabrication process is highly reproducible, as the efficiency of eighteen modules fabricated in one batch, showed standard deviation < 1% showing promise in translating perovskite from laboratory to industrial scale.

Project 4: Chalcogenide Solar Cells

The family of compound materials of copper-indium-gallium-diselenide known as CIGS [including Cu(In,Ga)Se₂, Cu(In,Ga)(S,Se)₂, CuIn(S,Se)₂, CuZnSn(S,Se)₂] have been investigated as absorber materials for thin film solar cells in the past decades, due to their high absorption coefficient and suitable bandgap for solar absorption.

The state of the art CIGS solar cells are typically fabricated using vacuum-based deposition techniques. The group’s earlier research focused on the development of solution-processed semiconducting materials for printable CIGS solar cells by means of spin coating and spray pyrolysis. We have successfully fabricated CIGS solar cells with >10% efficiency, which is one of the highest reported for water-based solution processed thin films [J. Mater. Chem. A, 2015, 8, 4147-4154 (inside front cover)]. Also, we have identified the key synthesis parameters required to produce single phase wurtzite CuZnSnS₂ (CZTS) [JACS, 2014, 136 (18), 6684-6692]. The next task is to scale up the production in order to fabricate solar cells with active areas of at least 25 cm². Cells of this size are comparable to commercial cells and will demonstrate the scalability of the processes developed.

We are currently optimizing our thin film deposition technique to fabricate such devices. An example of a large area device is shown in Figure 4. Subsequently, modification of post-film deposition annealing, the deposition of transparent conducting film, and the design of top electrode for optimum collection efficiency are investigated. We also take the opportunity to improve some steps in the process to obtain better control of film quality as we expand our process capabilities with new equipment acquisitions. As this thin film solar cell shows excellent air stability, it will be used in subsequent demonstration in PV-powered sensor and proof-of-concept aesthetic solar cell for building applications. We also recently used Cd doping into CuZnSnS₂ to make record Cu-sulfide based thin film solar cell with efficiency of > 9% [Adv. Energy Mater., 2015, DOI:10.1002/ aenm.201500682]. We postulate that Cd doping will displace Zn and reduce the formation of Cu-Zn anti-site defects in the CZTS films, thereby improving device open circuit voltage and power conversion efficiency. These improved cells share the low cost fabrication process of CZTS and can be scaled for deposition on flexible substrate and exhibiting excellent air stability. Future work in this area is directed at extending the search for alternative cation substitutes which are low in toxicity and earth abundant.
**Project 5: Solar Fuels**

Efficient water splitting driven by a single photoelectrode has remained elusive due to stringent electronic and thermodynamic property requirements. A few materials have been identified as potential photoanode materials. Yet, their performance has been limited by low carrier concentration and poor electronic properties that required a high over potential for water oxidation and low STH efficiency. Efficient water splitting using a photoactive anode could be realised by connecting it in series with a solar cell which could provide part of the required over potential. Our researchers showed that a modified hematite ($\alpha$-Fe2O3) coated on FTO substrate could be used as a semi-transparent anode in tandem with a perovskite solar cell [Nanoletters, 2015, 15 (6), 3833-3839]. Emphasizing the tandem concept, they chose an architecture that required light to pass through the anode and the transmitted light was used to energise the solar cell.

Because some of the incident light was absorbed by the anode, the solar cell was required to have an extended optical absorption up to ~800 nm to be efficient (Figure 5; manuscript under review). Production of a high open circuit voltage by the solar cell is advantageous as this would assist in the anode reaching the required over potential. In addition to tandem configurations, scaling up of photoanodes for large area demonstrators was also performed. Besides hematite ($\alpha$-Fe2O3), WO3 and BiVO4 were also scaled up to >40 cm2 area.

CO2 reduction to form hydrocarbons requires a catalyst surface for CO2 and intermediate species adsorptions and involves multiple steps of hydrogenation to produce various hydrocarbons, such as CO, CH4, C2H4, etc. A highly selective electrode has been developed for producing formic acid from CO2. The Cu electrode is modified by phosphate ligands, which promoted the hydrogen addition to CO2 molecule for formic acid production. Other approaches include the utilisation of metal-organic frameworks (MOFs) for selective adsorption of the reactant products to induce superior selectivity.

![Figure 5. Left: Schematic of tandem cell featuring a perovskite solar cell and CoP/I/ 20 ALD cycles hematite photoanode, Right: standard solar AM 1.5G photon flux and incident photon flux for solar cell. The shaded areas are electron flux from CoP/I/ SnOx treated (20 ALD cycles) hematite and perovskite solar cell used to calculate the integrated photocurrent density. The cell has a solar-to-hydrogen (STH) efficiency of 3.4%.](image)
Current global efforts in developing wind turbine and ocean energy systems towards temperate climate focus mainly on the markets of Europe and North America’s geographical conditions. However, there is a growing energy need in Asia, which specifically experiences relatively lower wind velocity and tidal resource conditions. ERI@N’s W&M research team hence primarily focuses toward developing right technologies and W&M systems for tropical conditions as well in support of the remote coastal and islandic energy needs as alternative energy sources. In addition, the W&M team also collaborates with industrial partners for developing the right computational design tools and technological solutions to support field based W&M resource mapping, large scale wind & tidal energy systems, reliability studies involving fatigue, wear & tribology issues and advanced materials & manufacturing processes such as: high strength low weight composites, additive manufacturing & laser based surface treatment methods.

The W&M team established a continuing joint industry programme (JIP) between the leading industries in offshore renewables and academia to support masters and doctoral level research. Today, more than 10 masters and 24 doctoral students focus on various research topics under low technology readiness level (TRL 1-3) related to W&M energy. In parallel the team develops unique products to meet the regional needs and international offshore renewables’ technology needs. To support this work W&M team has secured more than $54.5 million from competitive research grants and $33.5 million from industries for the wind and marine energy basic and applied research studies.

Programme at a glance

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</tbody>
</table>

In order to cultivate a regional new market, the team collaborates with various research institutes in countries that are part of ASEAN and has setup a virtual collaboration network called SEACORE. This initiative has been recognized by the ASEAN Centre for Energy based in Jakarta as the official work group for offshore renewables for ASEAN. The team also works closely with the Sustainable Energy Association of Singapore (SEAS) to promote Singapore based multinational subsidiaries and SMEs to collaborate in the W&M renewable development and develop useful supply chain to meet the regional demands. Furthermore, the team works closely with Singapore standards to form useful standards and design guidelines to suit tropical regional needs of South East Asia. This fact has gained global attention such that the European and North American partners are interested in collaborating to alter the turbines and test in Singapore’s resource conditions before deploying in the South East Asian market and other tropical regions.
Project 1: Low flow Wind Turbine

Wind turbines available in the market today start to generate power only when the wind speed reaches above 4 m/s. Thus, for countries with low wind speed such as Singapore and most Asian countries, the maximum wind speed is aimed to be 8 m/s and turbines available in the market will stay idle for most of the time producing negligible power. Hence, tropical region demands for wind turbines that have low 'cut-in' wind speed with light weight rotors and systems such that they deliver rated power at 8 m/sec and can easily suit remote region’s logistics and transportation constraints.

Small wind turbine market has not been kicked off yet in Asian region. However, there is a huge potential if the wind turbines are able to generate power at a low wind speed of less than 8 m/s, which is prevalent in these regions at an affordable cost of energy at par to the diesel cost ($0.4/KWh) for the following applications as shown in Figure 6. Wind turbines developed in the US and European countries are not affordable due to longer return of investment and not suited for the Southeast Asian tropical wind conditions. Accordingly, ERI@N’s ongoing research objective revolves around developing small wind turbines (<100 kw) for the average wind speed of 6 m/s at a cost of 75 % as compared to currently available models.

The research focus of this project lies in:

- Multi-criteria optimization of aerofoil selection to achieve high performance low inertial wind turbine blade structure
- Incorporating natural fibres integrated with synthetic fibres in the composite design to enable wind turbine rotors to achieve minimal inertia and also to meet sustainability and low cost requirements.
- Integrating Compressed Air Energy Storage in the wind turbine drive train system to act as a suitable energy storage option at wind turbine level.
- Electric start-up capabilities to overcome inertial and static friction to minimize ‘cut-in’ speeds.
- Low inertial drive train design using light weight metal alloys.

Product development methodology

- The key aspect in achieving a low flow turbine is to minimize rotor inertia by enabling lower blade mass through adoption of light weight material.
- Aerodynamic design optimization for 3D modelling, load estimation, layup design, tip deflection and strain estimation are carried out until the deflection is within the acceptable range.
- In order to test and evaluate the blades, the proposed fiber-matrix system (such as low modulus carbon blade and/or Hemp fiber) with lower solidity and thickness using pre-preg materials are studied at coupon and further tested at blade level.
- Drive train modification and low cost gearbox introduction for small wind turbine
- In order to be safe to be deployed in open environment, the rotor and tower structural designs are evaluated as per the IEC and GL design guidelines. According to these guidelines turbines for sites with 6 m/s average wind speed, should be stiff enough to maintain a tower clearance of >30% at all wind speeds. So, an extreme wind speed of 31.5 m/s (IEC Extreme wind speed model, 01-year average) which are greater than the region’s extreme and the cut-out speed of 18 m/s are chosen. To meet the remote region’s lack of infrastructure and occasional typhoons (such as in Philippines) the project focuses to provide self-erecting feature for the tower such that it can be brought down to ground level after cut-out wind speeds.

Project Outcomes

To develop a wind turbine that is capable of generating power at low wind speed, the drive is integrated with innovative concepts such as electric start-up and compressed air energy storage design. The self-installing tower as shown in Figure 7 with counter weight for crane free installation is being designed such that the need for robust materials and structural design for high wind speed can be avoided. Such feature will help reduce the turbine weight and aid in easy transportation. Another important feature is to incorporate the wind turbine with compressed air energy storage to minimize wind intermittency.

Current Status

The team has successfully demonstrated a 2 KW wind turbine in Tuas, Singapore and incorporated with a Nano-grid system. Presently research is in progress towards a 10 KW wind turbine to suit Singapore’s Semakau island site conditions. In terms of vertical axis turbine, to enable self-starting and low inertia novelty has been achieved and has been submitted for IP disclosure:
- Savonius turbine with Magnetic torque transmission (Accepted for full patent)
- Vertical axis hybrid turbine (TD to be submitted).
Project 2: Low Flow In-stream Tidal Turbine

Next generation tidal turbines are generally designed to capture higher energy content available in the faster tidal currents that occur in the upper water column of tidal flows and to reduce higher installation costs of the foundation. The competitive edge of next generation tidal turbine designs is in fact, those that are able to operate in deeper waters as well as in shallow waters due to their novel deployment technologies.

Until now, little research has been conducted on low-flow tidal instream energy (TISE) resource conditions to ensure that the turbine systems will be robust, efficient and economical, especially for tropical waters conditions of South East Asia (SEA). Most of the current research interests in tidal turbine lie within the gravity-based foundation; tripod and mono-pile structures designed for megawatt-scale (MW) turbines, which involves deep dive support, clearance to work in shipping straits and other maritime users. Hence, the idea of easy tovable design that can support rapid deployment technologies needs detailed attention to convert into useful products for meeting remote coastal and islandic needs specifically towards shallow water regions.

Smaller tidal instream energy (TISE) devices, that produce less power and are less expensive, provide a solution for many remote communities (with only hundreds of households) with not an extensive demand for energy at a low cost. Marine hydrokinetic energy in the water column of tidal flows varies with depth. The upper 50% of the water depth contains 75% of the total energy available in the water column. If smaller tidal turbines are installed in the lower 50% of the water depth, the energy content would be merely 25% of the total energy available in the water column and the rotors will suffer uncertainty in loadings due to the turbulence boundary layer of the seabed and unsteady flow patterns in the vertical water column near the seabed. The rapidly deployable and buoyant tidal turbine (to capture the higher energy at the upper water column) solution is an important component of this project as there is a huge market potential in the region.

Project Outcomes
To develop a ‘semi-buoyant’ tidal turbine system that is well-suited to 4 to 6 Knots of water current and has necessary features to meet tropical region environmental challenges.

The project focuses in the following basic research:
- To develop novel hydrofoil through multi-level optimization using Artificial Intelligence Techniques towards enhancing lift characteristics and structural rigidity, while minimizing drag, cavitation and underwater noise.
- To investigate the hydrodynamics of the tidal turbine system to match it in accordance with tidal energy resource specifications and site specific challenges such as seaweed anti-entanglement.
- To enhance environment resistance through hydrophobic marine safe protective coating to minimize biofouling resistance and simultaneously enhancing erosion resistance.
- To perform mooring dynamics studies using novel composite fibres (such as Dyneema) as against conventional steel rope and chain type system.

Product Development Methodology
- Developing a tidal turbine of 1m diameter to check for turbine performance
- Developing an anti-sea weed entanglement blade through the design of a rake angle turbine rotor system, shown in Figure 8a
- Integrating a barge based system with the scaled turbine of up to 5m diameter in tune to the site’s tidal resource condition
- Performing necessary barge dynamics studies using hydrodynamics and fluid-structure interaction studies to ensure that the Heave, Surge, Sway and Roll, Pitch and Yaw characteristics are within the performance limits of the turbine system
- Identifying the right mooring system to ensure it provides necessary constraints to the Barge-Turbine dynamics under the site’s maximum tidal and wave condition
- Developing the biofouling resistive coating that ensures necessary turbulence resistance under erosive condition.

Current Status
- Developed an anti-sea weed entanglement blade through the design of a rake angle turbine rotor system and manufactured by novel rapid prototyping and cement based mold method as shown in Figure 8a.

- A 5m diameter tidal turbine was integrated in a commercial barge system with special retractable support structure and has been deployed in Indonesian waters (shown in Figure 9).

Figure 8a. (left to right) Design of rake angle turbine, steps in typical tidal turbine manufacturing with novel rapid prototyping and cement based mold method and Figure 8b. deployment of the turbine in Singapore

Figure 9: Design and deployment of the barge based tidal turbine system, presently deployed and tested in Indonesia.
Project 3: Tidal Resource Mapping System - MemBoat

Resource assessment and environmental impact assessment (EIA) is generally carried out by manual methods of deploying deep divers to install Acoustic Doppler Sensor system and other devices on seabed (see Figure 10). This requires clearances from the approval agencies if it is near shipping lanes and becomes challenging when their energy source is purely battery based systems with local data storage. Accessibility to these seabed sensors becomes difficult when excessive tidal current or marine mammals topple the sensors. Also in present day practice, transect analysis of resource mapping are performed by manual boats to acquire marine resource mapping along straight lines which requires the boats to perform few hundreds of repetitions, which is time consuming and inefficient.

Accordingly, this project aims to develop an Autonomous marine resource mapping vessel (MEMBoat) for data acquisition on the open sea and assess the renewable energy available on that area. Earlier studies with autonomous vessel were focused on rescue, oceanography survey, and water sample collection. The present application directly relates to marine renewable resource assessment.

Due to the increasing research and commercial activities in marine renewables, marine renewable resource assessment is becoming a key research area. Thus, the MEMBoat could serve as an essential tool to facilitate the assessment and, in the meantime, it can also serve as a base platform for researchers to customize.

The significances of MEMBoat are revealed in two aspects: MEMBoat platform and the data analysis system. MEMBoat is advantageous (when the hardware platforms are compared with traditional man powered methods over the competitors in terms of long-term stationary measurements and especially for their cooperative behaviour. In addition, MEMBoat’s data analysis system has clear advantages in terms of spatial correlated data acquisition and real time data playback. Such features facilitate the researchers to further customize data acquisition capability.

Project Research Focus
• To identify the right sensor systems and perform signal analysis to characterize the tidal current of the specific ocean site
• To characterize the seabed morphology through a roving acoustic Doppler sensing system
• To study the wave amplitude & frequency and characterize their depth behaviour, investigate the hydrodynamics behaviour of the scanning vessel, to identify the allowable roving specifications in tune to operational needs of the data acquisition sensor system under dynamic ocean conditions.

Product development methodology
To perform optimized vessel shape using naval architectural principles, and detailed vessel dynamics using hydrodynamics & support structure studies by incorporating field level measurements of wave and tidal flow conditions, seabed morphology, mooring design details, barge material and design conditions, etc.

Research Outcomes
The project aims to deliver an autonomous resource mapping system, capable of characterizing a remote condition without manual deep diver support for the installation of sensors, such as acoustic Doppler current profiling system (ADCP), used for measuring tidal current conditions, seabed morphology, and necessary transect analysis etc. Accordingly, the following technical details will be the specific outcomes:
• identifying right sensors and to integrate into a system
• overall controller design: structure and software suite
• power management & security system
• drag minimizing design for MemBoat with best dynamic stability to sustain the wave and tidal currents within the sensor’s operational limits
• tidal and wave energy resource mapping method of shallow water remote sites along with their seabed bathymetry

Present progress
• The team has successfully developed an autonomous robotic system (Figure 11) that can support ADCP sensor system and perform necessary transect analysis
• Developed novel Architecture of Sensor network for Resource mapping, and forecasting algorithms and software
• Based on these prototype studies, a more elegant design is being developed, with smaller footprint and carrying higher pay load of 10 kg sensors with higher scanning speed.

Figure 10 : Typical manual mounting of ADCP sensors on seabed by deep divers

Figure 11 : First and Second prototype of the autonomous resource mapping robot under study
Project 4: Tribology of Wind turbine components

Among the most adverse failures, in terms of downtime, of wind turbine components such as generator, gearbox, electrical system and rotor, etc., gearbox failure ranks top according to a study by NREL (USA), leading to increased cost of energy for wind turbine companies.

The predominant reasons for gearbox failures are related materials, for instance: pitting of planetary bearings caused by rolling contact fatigue, manufacturing defects such as non-metallic inclusions caused by oxidation process, microstructural banding in case hardened layers resulting from poor heat treatment methods; all of which serve as nucleation sites for mechanical failures. Hence, there is a key necessity of gearbox material improvement to facilitate increased gearbox reliability and decreased cost of energy.

Traditionally, case hardening depths of 2 mm are attained by conventional carburizing methods and are already proven to be inefficient for gearboxes even up to 3 MW capacity to meet the 20 years of product life which results in premature failures. However, the industry is scaling towards 10 MW wind turbine which demands for gears with 6 mm case depths to resist necessary contact stresses between gears.

Research focus

Major focus of this project is to introduce excessive compressive residual stresses at surface and subsurface depths of the gears for improved hardenability. To achieve this, the following approaches (as shown in Figure 12) are identified:

1. Laser surface hardening (LSH) to promote higher thermal gradients leading to self-quenching rates of > 1000 °C/sec resulting in a martensitic microstructure. LSH also offers the flexibility of site specific hardening by reaching complex geometries of the gears along with possibility towards on-site repair/modification facility. A systematic study of LSH process optimization for wind turbine gears and validation against traditional case-hardening methods followed by wind turbine gear manufacturers will be executed along with cost comparison.

2. Conventional case hardening steels such as 18CrNiMo6 used by many wind turbine companies for gears consist of high alloy compositions with expensive elements such as nickel. However, alloying elements like boron even as a trace element (0.0002 – 0.005 % by weight) offers increased hardenability as compared to higher concentrations of carbon; and concentration of molybdenum is varied for improved toughness, in turn enhancing the wear and tribological properties of steels. Hence, steels with such alloying elements will be treated as potential gear materials and heat treatment methods will be applied for microstructural engineering.

3. Advanced multi-functional coatings such as Diamond like Carbon (DLC) will be applied on the existing and improved gear materials to enhance their performance and further increase the gear life span.

Research Methodology

Tribological property measurements will be carried out on LSH, multi-functional coated and improved gear material specimens by subjecting them to contact stresses, sliding speed, lubricant, and environmental conditions on lab based specimens (such as pin and ball on disk tribometer experiments), as well as gears will be manufactured to mimic the real time load conditions in the laboratory gear test rig. Once the samples meet the tribological test conditions the material, coating and heat treatment choices will be studied on the gears in a scaled gearbox condition and its real time wear characteristics will be observed.

Project outcome

With increasing geometric scaling of the wind turbine rotors, gearbox failure has become a great concern. The outcomes of this project will serve as a guide for cost effective steels for gears as compared to traditional relatively expensive case-hardening steels. The alternate bulk materials proposed will also be superior in tribological properties suitable for wind turbine gears and other applications where wear and abrasion are challenging issues. A protocol for LSH process methodology will be delivered which can be adapted for surface hardening of gears, along with cost comparison studies.

Present efforts

- Full field simulation of large scale turbine (> 5 MW) using FAST simulation software to identify the drive train dynamics and contact forces on gear pair of the gearbox are further converted to contact stresses, slip, and other operating loads to be applied in to the tribometer experiments.
- In parallel, identifying alternate bulk gear material and laser surface heat treatment are being actively looked into.
**Project 5: Additive Manufacturing of Fatigue Resistant Wind turbine components**

Generic wind turbine components are designed for extreme wind load conditions and predominantly undergo premature failures as the material requirements can’t meet specific atmospheres such as turbulent wind conditions acting as low frequency cyclic loads. Wind turbine components either majorly made of cast iron (axial stresses) or high alloyed steel such as 34CrNiMo7-6 (bending and axial stresses) undergoes similar failures. This has opened a potential window for tailoring steel/alloy composition for improved fatigue strength.

The main aim of this project is to tailor/develop a new steel composition with improved fatigue properties. Focus is also on improving methods such as additive manufacturing (AM) / 3D printing for wind turbines to enable faster replacement of failed complex components.

**Methodology**

- Conventional strengthening mechanisms such as precipitation hardening, grain size refinement and multi-phase crystallographic structure enable enhanced mechanical properties in poly-crystalline materials. This can be achieved by (i) either alloy engineering or (ii) austenitizing steel/iron and following a time temperature transformation and/or continuous cooling methods or (iii) a combination of the latter two methods.

- In addition, molecular dynamics based simulations project the effects of alloying elements for varying stress/load conditions which can be input into determining the weight percentages of the alloying elements for experimental methods of making steel coupons.

- Advanced manufacturing methods such as additive manufacturing provide a better alternative to the failed traditional wind turbine components in meeting the existing customer demand with maintenance issues due to fatigue failure. Mechanical test coupons such as tensile and fatigue specimens according to ASTM standards are made through selective laser melting type additive manufacturing routes.

- Studying the role of alloying elements will be complimented by systematic variation of their concentrations and supported by advanced characterization techniques such as high resolution electron microscopy.

- Further 3D printing of actual wind turbine components will be carried out to its dimensional and surface quality.

**Project Outcome**

- This project delivers a new generation steel alloy composition with improved cyclic fatigue properties and to suit additive manufacturing processes.

- Furthermore, the ability to analyse fatigue behaviour of wind turbine components using dynamic tensile test and prediction of service lifetime can be achieved and support the new component designs for the industrial designer.

- The tailored composition delivered by this project is checked for suitability for other structural applications than wind turbine components.

**Current status**

A steel composition has been chosen for printing ASTM E466 size test coupons by additive manufacturing as shown in Figure 13a. Complete mechanical testing was carried out along with failure analysis. Fatigue testing results are shown in Figure 13b, c, and d. Current experimental results show that additive manufactured specimens with high orders of anisotropy and irregular microstructural features also fail in a conventional way (dimpled ductile fracture) similar to their traditionally manufactured (forged steel A specimens) counterparts and further open a window to tailor mechanical properties by following conventional strengthening mechanisms. Fatigue strength of steel A investigated in this project is comparable and significantly higher than traditionally manufactured cast iron, posing AM as a potential candidate for structural components.

![Figure 13](image-url)
ERI@N’s Energy Storage programme develops advanced electrochemical charge storage systems (ECSSs) to meet the current and future demands for a variety of distinct applications. A wide range of technologies are supported by the programme, including but not limited to: lithium ion batteries, beyond lithium technologies, next generation supercapacitors, flow batteries for large scale grid storage systems, and advanced batteries for high power applications such as electric vehicles. Each of these fields presents a unique set of criteria for which ECSSs must be tailored. The institute works closely with industrial partners and academic research institutions (both Singaporean and international) to deliver improvements to current ECSSs and develop future-focused solutions to support a myriad of energy needs and remain at the vanguard of energy storage technology.

The Energy Storage programme is comprised of approximately 30 researchers, students and staff stationed both on NTU campus, at the Research Techno Plaza and at the department of Material Science and Engineering, and off-campus, at nearby CleanTech One. This structure provides an excellent framework for coupling the development of new technologies, with the in-house facilities to investigate the scale-up of these technologies to test industrial viability in the new Prototyping Lab at CleanTech One.

Recent achievements in the optimisation of next generation Li-ion materials at ERI@N include i) the development of fast charging anodes and high capacity cathodes (Tang, et al 2014), (ii) improved cycle stability of electrodes (Banerjee, et. al) and iii) the development of electrochemical thermodynamics method (ETM) for determining state-of-safety of a battery (Maher and Yazami 2014). On-going projects and previous partnerships include companies as BMW, Johnson Matthey, Clariant and New resources technology (Durapower) in developing next generation lithium ion battery materials.

Several exciting alternatives to Li-ion chemistry are being investigated to garner step-changes in either increased energy density or lower cost. Fluoride-ion batteries can potentially store up to four times more energy than Li-ion batteries per weight, due to the possibility of high fluorine content in both anode and cathode materials compared to their lithium counterparts. However, many challenges such as finding a suitable liquid electrolyte, have impeded development and must be overcome for the realisation of F-ion batteries.

Li-air systems are also of particular interest because of their high theoretical energy density (>10 kWh/kg). A new liquid state anode (or lithium solvated electron solution, LiSES) has been developed at ERI@N for advancement of Li-air batteries and other systems that benefit from this unique high energy density type of anode (Tan, et al 2012). A solid state electrolyte membrane (glass ceramic lithium aluminium germanium phosphate, LAGP) is also being developed as part of this effort.

Supercapacitors (SCs) currently fill the gap between batteries and conventional solid state or electrolytic capacitors. Research efforts focus on i) the combination of high surface area carbon materials with nanostructured transition metal oxides to increase power densities and energy densities respectively and ii) use of lithium intercalating electrodes (battery-type) to capitalise on the high energy density of Li-ions in supercapacitor systems. Promising materials are being scaled up to make capacitors of interest to industrial applications.

The ES research team developed a prototype vanadium redox flow battery (VRFB) with 2.5kW-10kWh output power and energy capacity, which was subsequently demonstrated to power a forklift. The team explored a second generation electrolyte to increase energy density of VRFB. It also developed novel combined additives for improving thermal stability and energy density of electrolyte. In a collaboration project with a commercial industry partner, a 10kw–100kWh commercial scale VRFB system was installed and integrated with solar PV and loads in a building for testing its performance in microgrid and grid connected applications.
Project 1: Fast charging materials for Lithium-ion batteries

Lithium-ion batteries usually use additives to bind the electrodes to the anode, which affects the speed in which electrons and ions can transfer in and out of the batteries. However, cross-linked titanium dioxide nanotube-based electrodes, developed at NTU, eliminate the need for these additives and can pack more energy into the same amount of space.

A major thrust is to produce advanced nanostructured anode and cathode materials with unique morphologies that maximise capacity, enables fast charging, and cycle stability. Figures 14 and 15 illustrate the variety of materials developed. One example of such is a fast charging battery material based on TiO2 that can be recharged up to 70 per cent in only 2 minutes. The battery will also have a longer lifespan of over 20 years. The new gel anode material made from titanium dioxide, an abundant, cheap and safe material. It is commonly used as a food additive or in sunscreen lotions to absorb harmful ultraviolet rays.

Naturally found in a spherical shape, a method was developed to turn titanium dioxide particles (Figure 16) into tiny nanotubes that are a thousand times thinner than the diameter of a human hair. This nanostructure is what helps to speeds up the chemical reactions taking place in the new battery, allowing for superfast charging. The team is setting up partnerships with lithium battery companies which are battery system integrator and energy storage providers. The fast charging technologies will be demonstrated through integration into their current commercial lithium-ion batteries utilising lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) using ERI@N’s prototyping facilities.

Fig. 14 Voltage and capacity of novel nanostructured cathodes and anodes

Fig. 15 SEM images of various electrode materials developed at ERIAN

Fig. 16 Results from proof-of-principle studies, a) image of the nanotube gels prepared by our technology and conventional method and SEM images of the as synthesized ultralong TiO2 nanotubes; b) long term cycling performances at high current density of 25 C up to 10,000 cycles (25 C refers to charging time in 2.4 min); c) performance comparison of ultralong TiO2 materials with graphite, Li4Ti5O12 and conventional TiO2 materials (1 C refers to charging time in 1 h, 10 C refers to charging time in 6 min).
It is well known that lithium ion batteries experience a natural decrease in energy storage performance upon cycling and usage. This is because battery cycling leads to increase in internal resistances, decrease in average discharge potential and decrease in discharge capacity and power output. Parameters such as cycle number, depth of charge and discharge, rates, overcharge and temperature are some of the most important factors which control the changes in battery performance. Degradation of electrode and electrolyte materials and loss of contact are a few of the many reasons of loss of performance. Therefore, it is important that a cheap and simple measurement system is developed to investigate the state of health and state of safety of the battery, in order to improve the overall electrochemical performance of lithium ion battery and prevent any possible risks.

In recent years our group has developed electrochemical thermodynamics measurements (ETM) methods and tools, to monitor the evolution of the thermodynamics behaviour and correlate it with changes in the structure of electrodes materials as they degrade. ETM is used as a new and non-destructive investigation tool to characterize the degradation level of electrode materials and consequently assess the cell’s state of health (SOH).

The team has developed a non-destructive and affordable method, combining ETM and computational data fitting algorithms, to determine the actual lithium composition in anode and cathode as a function of the cell SOC. ETM consists of monitoring the evolution of the cell’s open-circuit potential (OCP), with temperature at different states of charge (SOC).

The entropy $\Delta S(x)$ and enthalpy $\Delta H(x)$ state functions can be computed from the general thermodynamics laws:

$$\Delta S(x) = F \frac{\delta E_0(x)}{\delta T}$$

$$\Delta S(x) = -F(E_0 + T \frac{\delta E_0(x)}{\delta T})$$

Since $\Delta S(x)$ and $\Delta H(x)$ in the above equations are measured at a defined state of charge of the battery, ‘$x$’, $\Delta S(x)$ and $\Delta H(x)$ can be defined as the local slope of the battery system’ total entropy and the total enthalpy variation vs. ‘$x$’, respectively. Accordingly, there is no need for a reference state to determine $\Delta S(x)$ and $\Delta H(x)$.

Entropy and enthalpy profiles of LIB with the degradation degree of the respective electrode materials during aging are then generated and analysed. This is clearly illustrated in Figure 17 which shows entropy profile changes during a LIB cycle ageing at 55 °C. During ageing, differences are more noticeable in thermodynamics data profiles vs. SOC than vs. OCP. The SOH of cells decreased by 8% when cells were aged at 25°C for up to 500 cycles and by 9% for cells aged at 55°C for up to 400 cycles.

The thermodynamic profiles changes are used as a battery “fingerprint” to determine the cell’s chemistry and to assist the battery’s state of health (SOH) and state of safety (SOS).

In another project, the new method developed by the team, combining ETM and computational data fitting algorithms, enables accurate assessment of the lithium composition in anode and cathode. The main finding is that none of the anode and cathode operates at their full range of Li composition.

![Figure 17 Entropy vs. SOC (a) and OCP (b) profiles of LIB cells: NC (unaged) and aged cells at 55°C for 100, 200 and 300 cycles (HT100, HT200 and HT300)](image)
Project 3: Beyond Lithium Technologies

1. Lithium-fluoride ion battery
The concept of fluoride ion batteries (FiB) can be schematised as a mirror chemistry to lithium ion batteries (LIB), in which F⁻ anion plays a symmetric role to Li⁺ cation. Fluorine is more abundant and is 2-order of magnitude cheaper than lithium. Because of larger fluorine content ranges in anode and cathode FiB should provide twice the energy density of LIB. While our initial effort was directed towards developing stable anode, cathode and electrolyte materials for FiB, serendipity makes it that our choice of anode materials showed excellent characteristics as a cathode material for lithium-fluoride ion rechargeable batteries.

Solid solution mixed transition metal fluorides NiₓCo₁₋ₓF₂ were prepared for the first time and used as the cathode material in lithium-metal anode cells. Figure 18 shows the cycle capacity profiles for different x compositions. Good cycle performances are achieved, which makes the Li/ NiₓCo₁₋ₓF₂ rechargeable cells suitable for low voltage applications such as in hearing aid devices. Patents have been filed for this work (PCT/ SG2015/000008, US Patent Application No: 15/111,596).

Advantages of a liquid anode include i) fast ion transport capability ii) stable anode/ceramic membrane electrolyte interface and iii) fast “recharge”. A battery for electric vehicles (EVs) which utilises both liquid-state anode and cathode may permit refueling in a matter of minutes (instead of 3-8 hours recharging) by replacing the spent products with fresh electrode solutions. The structure of the proposed Li-SES system is shown in Figure 20 (Anolyte: Liquid Anode, Catholyte: Liquid Cathode).

At the current stage, a new catholyte solution (I₂) is being developed which allows for a full Li-SES cell to operate in an environment without oxygen. The new cell has undergone preliminary charge/discharge tests successfully. The anode is based on lithium solvated electron solution (Li-SES), whereas the cathode consists of an air electrode or a dissolved highly oxidizing species such as iodine. Liquid anode and cathode are separated by a lithium superionic conducting ceramics.

LISES are prepared by dissolving metallic lithium in a solution consisting of an electron receptor such as a polyaromatic hydrocarbon (PAH) in an ether solvent (i.e. tetrahydrofuran, THF). Another option to make a LiSES is by electrochemical reduction of lithium ion in a PAH-THF solution (electrochemical charge). Both methods were proven to be efficient.

2. Refillable lithium battery with liquid anode and liquid cathode
One major limitation of current lithium ion batteries is a long charging time, which is inconvenient for electric vehicles applications. Charging time is mainly controlled by ion diffusion in solid electrodes. To address the issue, we developed a new concept of refillable lithium batteries in which both anode and cathode are in the liquid state. This allows fast charging the battery by emptying and refilling the anode and cathode tanks at refill stations similar to current gas stations. Currently, rechargeable Li-air battery research focuses mostly on solid-state anode materials. However, the research team have chosen a unique route by developing a new type of liquid anode, which consists of lithium metal dissolved in a solution of electron receptors to form a lithium solvated electron solution (LiSES). Electron receptors used for this project are poly-aromatic hydrocarbons (PAH) such as biphenyl and naphthalene. This novel LiSES-air cell is particularly attractive as it can operate at ambient temperature.
3. Sodium ion batteries
The re-emergence of low-cost sodium-ion batteries (NIBs) has since generated a surge in research interest due to its similar chemistry with lithium-ion batteries (LIBs). Despite similar chemistry with Li, the different structural changes and interfacial properties of same materials in both systems are unique of one another. The key challenges in NIBs include developing materials with high specific capacity, long cycability, low cost and high conductivity. The larger size of Na ions translates into heavier mass, making NIBs best suitable as low-cost large scale energy storage application when coupled with other energy harvesting technologies such as solar cells or wind turbines. This project mainly investigates different anode materials in half cell setup for use in NIBs.

Anode materials for NIBs were selected from several different parameters including: i) high specific capacity; ii) long term cyclability; iii) low cost; iv) fast charging. Following the selection, methods for the synthesis of such anode materials will be evaluated with ease of preparation and cost being considered.

Following the synthesis, materials were coated onto current collectors (i.e aluminium foil) for half-cell testing. While commercial electrolytes for NIBs are not out in the market yet, we turned to the most commonly reported electrolyte (i.e. NaClO4 in PC and 5 wt% FEC) which was prepared in-house. Half-cells were assembled in argon filled glove box, with water and oxygen levels <1 ppm. The objectives of this project include:
1. Long cycle charge/discharge cycling performance of anode materials in NIB set-up.
2. Ex-situ analyses to investigate the structural changes during cycling of electrode materials
3. Impact of electrolytes on long term cycling performance of electrode materials.
Project 4: Supercapacitors

Supercapacitors (SC) currently fill the gap between batteries and conventional solid state and electrolytic capacitors. They store hundreds or thousands times more charge than the latter due to a much larger surface area available for charge storage in SC. The power density and cycle life of SCs are extremely high; however, due to their lower energy density compared to batteries, the high amount of power will only be available for a very short duration. The following projects are the highlights of our R&D focus on supercapacitors.

1. Development of new electrode materials and design of novel hybrid systems combining faradic and capacitive electrodes to achieve impressive increase in the supercapacitors’ energy performance.

2. Hybrid electrochemical capacitor or Li-ion capacitor (LIC): LIC composed of the combined advantages of both Li-ion battery and electrical double layer capacitors. LIC is capable of delivering higher energy density than supercapacitors and high power capability than the Li-ion batteries. We explored several insertion materials and high surface area carbonaceous materials for LIC. We adopted three strategies to prepare the high surface area carbons like recycling the bio-mass precursor, chemical approach by carbonizing polymers and graphene nanosheets.

3. Na-ion capacitor: Few materials like Na2Ti3O7, V2O5, Na3V2(PO4)3 and hard carbon were explored as insertion host for the accommodation of Na+ by Faradaic process along with activated carbon as counter electrode. Materials for high energy and high power electrodes, for example, battery type graphene decorated NaTi2(PO4)3 and hard carbon form the bio mass precursor were developed. Similarly, on the counter side, bio-mass derived (coconut shell) high surface area mesoporous carbon as supercapacitor component were incorporated.

Collaboration projects with industry partners is being pursued with the main objective to select high performance materials that can be scaled up and demonstrated in a commercial supercapacitor. Possible applications include powering electric vehicles, either in tandem with battery or by itself for short range transportation and quick recharging. The successful outcome of the project is an in-house scaled up nanomaterial with a built-in, scale-up reactor, and the demonstration of 100 cm2 supercapacitor.

The high energy and power capability of the LIC’s are anticipated to replace the conventional supercapacitors, owing to the smaller in size (three times smaller than conventional supercapacitor) and lower cost to generate the desired energy density. R&D approaches in this project include:

- Preparing high surface area carbonaceous materials from bio-mass, which holds the advantages of hetero-atom doping, active oxygenated functionalities and high mesoporosity
- Instead of using traditional insertion metal oxides and sulphides, the utilization of such materials undergo either conversion or alloying or both to increase energy density

Na-ion capacitor technology is very new and anticipated to replace conventional supercapacitor, which is similar to Li-ion capacitors. It is necessary to develop the high rate Na-insertion type material and double layer forming high surface area carbons to realize the high energy and high power Na-ion capacitor assemblies. R&D approaches in this project include:

- Preparation of graphene based composites is beneficial in two ways, increasing the high power capability of the insertion host
- Functionalization of activated carbon is one of the important aspects to elevate the power density of Na-ion capacitors. Also, the hetero-atom doped graphene nanosheets is another important strategy to improve it
- Alloy anodes are another class of materials to be employed as promising high energy candidates. Implication of pre-sodiated alloy anodes is expected to enhance the energy density of Na-ion capacitors
- Usage of solid polymer electrolytes will be explored to develop leak proof and shape versatile Na-ion capacitors
Project 5: Vanadium Redox Flow Battery (VRFB) - R&D

Vanadium Redox Flow Battery (VRFB) constitutes one of the most promising options for future large-scale energy storage systems. Some of its benefits are high energy efficiency, long cycle life, safety, low capital cost and life cycle cost. VRFB employs the same vanadium element with sulphuric acid as supporting electrolyte in both half-cells, thus avoiding the problem of cross-contamination of the two half-cell electrolytes. This enables the electrolytes to be used indefinitely, hence eliminating the disposal issue, becoming therefore an environmentally friendly battery.

ERI@N has special interest, knowledge and expertise in the area of energy storage, more particularly on vanadium redox flow battery. Research efforts are focused on improved carbon-based electrode materials, cell and stack design, modelling and performance evaluation, thermal stability of electrolyte, and theoretical understanding of electrode-electrolyte interactions.

The key research elements pursued include the following:
1. Parametric study of carbon-based electrode materials for the application in VRFB - comprehensive electrochemical investigation of porous carbon materials in VRFB cells
2. Performance modelling and durability testing of carbon components in VRFB stacks
3. Development of a halide-free, stabilized VRFB electrolyte - Novel VRFB electrolyte with improved thermal stability
4. Investigating the functionality of VRFB and characterizing electrode and electrolyte properties at molecular level, via first-principles modelling - Modelling of carbon-electrolyte interactions and electrochemistry
FUEL CELLS

Hydrogen is perceived to be an ideal energy carrier with the potential to open up the door to a wide range of applications and policy options. On the other hand, fuel cells are energy conversion systems with high efficiencies, having a variety of applications in portable and stationary power supply. Hydrogen and fuel cells technologies have the potential to make major contributions to the key policy objectives of energy security and mitigation of carbon dioxide (CO2) emissions, given sufficient support. To-date, there are approximately 400 demonstration projects currently in progress worldwide.

Some of the potential applications in which fuel cell and hydrogen technologies can be deployed in Singapore to further reduce the emission and improve the energy efficiency are: grid storage and power distribution, grid balancing, transportation, emission control for generators, combined cooling, heat and power for buildings, back-up power for data centres, disaster relief application and on-site generation for remote sites such as islands.

Programme at a glance

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The fuel cell team has developed capabilities in polymer electrolyte membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC) and hydrogen related technologies, covering materials, catalysis and electro-chemistry, and thermo-fluid and design. Although fuel cell and hydrogen technologies have reached commercialization stage, it was cited in a recent industry report that the key issues that the industry is grappling with is the durability and the costs of the fuel cell, electrolyser and hydrogen energy storage. The durability and the costs issues are directly related to the costs and amount of the catalysts used in the systems. These issues are addressed by the on-going efforts in developing high performance, nano-sized catalysts for fuel cell and related technologies.

In order for the fuel oxidation and oxygen reduction reactions in a fuel cell to occur at desired electrochemical kinetic rates and potentials, highly active and durable electro-catalysts are required. Due to the high catalytic nature of platinum and its chemical stability, platinum and platinum alloy materials, supported or unsupported are preferred as electro-catalyst for the anode and cathodes in low-temperature fuel cells. A key challenge for the fuel cell industry is to reduce the catalyst cost while maintaining the performance stability. We are developing a system of noble and non-noble, nano-sized catalyst for various fuel cell applications, such as chlorine-tolerant catalysts for converting tainted hydrogen discharged from chlor-alkali plant as a by-product, and oxidant-stable catalysts in back-up powers. The competency is extended to hydrogen generation, where durability and rate of generation are important attributes.

The waste heat from the fuel cell system could be recovered for absorption chiller, thus, making synergetic combination to achieve overall system efficiency of >85%. The group focuses on system-level techno-economic analysis, financial and business analysis, system design & balance-of-plant (BoP) sizing and matching as these require in-depth understanding and knowledge of both fuel cell and thermodynamics.

Energy storage plays an important part in the electric grid system as the desire to improve the utilisation of variable renewable energies to above 20% of the grid capacity, the increase in dynamic and digital (non-linear) loads, the continuous differentiation of their requirements, and the increasing use of electricity in the transport sector, push the limits of the existing grid system. Energy storage can improve the power quality and reliability, reduce transmission losses and defer the transmission and distribution investment costs. Among all the energy storage technologies, the hydrogen energy storage is one of the most promising long term options, given that it is scalable in size, able to store large amount of energy in a compact space and versatile enough for different downstream applications.

In power-to-gas, the intent is to have the carbon dioxide discharged from refineries and (sea)water co-electrolysed to produce hydrogen and carbon monoxide. Syngas is the fundamental building block for numerous chemicals, and can be further processed to produce methane, methanol, diesel, wax, etc.
Project 1: Facile preparation of high Pt loading catalyst by microwave-assisted continuous flow reduction

Fuel cells are able to convert chemical energy from the oxidation of fuels directly to electrical energy and are considered to be one of the most promising clean energy conversion devices. Proton exchange membrane fuel cells (PEMFCs), a kind of low-temperature fuel cells, are characterized by the wide operating temperature range from -20 °C to 160 °C (depending on the solid electrolyte properties), quick start and response, and high output power density. These properties allow the PEMFC systems to be physically smaller and lighter. As such, PEMFCs are deemed to be suitable as the power source for vehicular, unmanned aerial vehicle (UAV), portable and stationary power applications.

The core of PEMFCs is the membrane-electrode assembly (MEA), which composed of a solid electrolyte sandwiched in between two catalytic electrodes. The electrode generally contains a catalyst layer, a macroporous layer and a backing layer. The catalyst layer can be applied directly on solid electrolyte, or supported on backing layer. The PEMFCs employ noble metals, especially, scarce platinum or its alloy supported on carbon materials as electrode catalysts to promote the reactions of fuel electro-oxidation and oxygen reduction. The high catalytic nature and chemical stability of platinum made it the ideal catalyst to be used in the oxidation and reduction conditions found in fuel cell.

In the hydrogen-fed PEMFCs, 50% of the stack cost came from electrodes, while catalyst contributes to 80% of the cost of electrodes, this implied that the catalyst contributes to 40% of the stack cost. Hence, it is imperative to reduce or eliminate the use of platinum in the cathode, which would lead to a more affordable fuel cell system as a whole and made it possible for commercialization.

The proposed project is to develop a continuous, rapid, feasible and reliable synthesis process for ultra-fine nano-sized catalysts with very high metallic loadings. The key advantage in this synthesis process over existing process is the continuous production of ultra-fine, nano-sized, high metallic loading catalyst without the use of surfactants that are difficult to remove. The other significant advantage is the decrease of energy and time in the catalyst production, which results in cheaper production cost. Besides these, the proposed synthesis process can significantly increase the surface reaction area and, hence, the effectiveness of catalyst utilization. The above-mentioned advantages have a critical impact on the fabrication of catalysts, especially for the noble metal catalysts, such as platinum (~USD1562/Oz) and palladium (~USD734/Oz). As an indication of the cost impact of catalysts on system, the supported platinum or platinum alloys catalysts used in low-temperature fuel cells contributes to around 40% of the total system cost. Platinum-based catalysts are also widely employed in various chemical reactions and industries. The potential commercial value and scalability of the synthesis process is further demonstrated through this project, where further research efforts are carried out on the process shown on Figure 24.
Project 2: Cobalt-based catalyst for NaBH₄

Proton exchange membrane fuel cell (PEMFC) is considered to be one of the most promising fuel cell technologies for vehicular, unmanned aerial vehicle (UAV), portable and stationary power applications. As the feedstock to the PEMFC, hydrogen (H₂) is an ideal fuel because it reacts with oxygen (O₂) to produce the electrical energy, and water (H₂O) as the sole by-product. Virtually no other harmful reaction by-products are produced in the exhaust of the PEMFC system. As a result, the use of hydrogen as a fuel effectively solves many environmental problems associated with the use of petroleum based fuels. However, the production and storage of hydrogen remain a problem. At present, high pressure vessels are the universal hydrogen storage method. However, this technique is not ideal for highly portable application such as the UAV, owing to the low hydrogen density (HD) and high weight of vessels.

Many studies to find effective storage materials have been performed. Among the various materials that have been intensively studied, the complex hydrides such as NaBH₄, LiBH₄, NaAlH₄, Mg(BH₄)₂, NH₃BH₃ are attractive hydrogen storage materials. These compounds currently have no competitors in terms of hydrogen content. Sodium borohydride (NaBH₄) has attracted attention (U.S. patent No. 2461662, 2461663, 2534553 and 2964378) because of its high content of hydrogen of as high as 10.7 wt.%, high stability of its alkali solutions, non-toxicity and fire-safety. In addition, this hydride is the least expensive and commercially available. Consequently, a prototype was constructed to demonstrate the hydrolysis of NaBH₄ (U.S. patent No. 6534033).

Different acids and metal-based systems have been studied as catalysts for this hydrolysis process. The catalysts containing noble metals Pt, Rh, Ru (supported or not) have shown the best performance. However, the high cost of these catalysts has initiated studies into the development of catalytic systems not requiring noble metals. Our technology scan in the field of hydrolysis of NaBH₄ determined that the Co-based catalysts are the next viable alternatives to noble metals, due to its high reactivity and cost effectiveness. The latest metal price comparison (Jun 2011) showed that Ruthenium (Ru) costs ~USD 180 per oz, while Cobalt (Co) costs only ~USD 16 per lb, or the price ratio of Ru to Co of 180! Different works on various forms of Co have been investigated including chloride, metallic, boride (B), alloys of B or nickel (Ni), doped with phosphorous (P), supported on carbon, resin, metal oxides or thin film. However, the cost of such nano-size cobalt-based catalysts is expensive and the “spent” catalysts cannot be easily separated and recycled. The durability of such nano-size cobalt-based catalysts is also less than desirable, which is the most critical issue in any application when the catalysts are envisaged for multiple very harsh start-stop applications. A glimpse of the required robustness of the catalysts is indicated in the U.S. patent 2570882, where it was reported that a crushing strength of ~4200 psi is needed for the precipitated cobalt carbonate.

A self-supported cobalt oxide-based catalyst was pioneered to accelerate the hydrolysis of sodium borohydride (NaBH₄) for the production of high purity hydrogen gas, which is extremely useful in many applications including as a fuel source for portable proton exchange membrane fuel cells (PEMFC). We have demonstrated that the cobalt-based catalyst is a promising alternative to other commercial catalysts, including precious metals such as Ru and Rh, owing to the high reactivity, cost effective, high durability (over 10 times more durable than Ru in lifespan) and recyclability. The developed cobalt oxide-based catalysts displayed the highest catalytic effect on the hydrolysis of sodium borohydride and are expected to exceed hydrogen generation rate of 1 L min⁻¹ g⁻¹ at reaction temperature lower 60°C for high-efficiency hydrogen generation system applications. We have also circumvented the technical challenges in producing small ceramic beads in bulk by applying novel gel-casting technique. It is a low capital investment and cost-effective technique, allowing the production of the self-supported cobalt oxide-based catalyst to be scaled up easily. The combinational effects of sintering additives, sintering temperatures and diameters of the catalytic beads on the hydrogen generation rate of the cobalt oxide-based catalysts is studied to understand the role of crystal structure of cobalt oxide on the catalytic efficiency, which is critical for optimizing the parameters associated with the scaling up production of catalyst beads, and the performance of hydrolysis of sodium borohydride.

![Figure 25 Gel-casting process for cobalt oxide spherical beads fabrication](image-url)
Project 3: Fuel cells as a power source for ship and port

Fuel cells, polymer electrolyte fuel cells (PEFCs) in particular, have been demonstrated successfully in mobile application such as the power plants for the vehicles. PEFC has also been used as stationary or portable power systems in many applications. However, many technical challenges remain in PEFC which restricts its life span. The harshest application of PEFC stack can be considered to be in automobile and the typical lifespan of a stack is between 2000 and 3000 hrs, though effort has been called for extending the lifespan to 5000 hrs. Thus, despite the attractive energy efficiency of PEFC, its short life span hinders the practical application. In addition, the performance stability of the fuel cell stack is also very critical during operation as overheating, dehydration of anode, flooding of cathode and dissolution of catalyst, etc., causing performance degradation, which leads to shortened lifespan of cell components and the fuel cell stack as a whole.

Despite solving the dehydration of anode issue, the problem of cathodic flooding remains. Our recent discovery on introducing silicone oil in cathode by emulsion method has proved to be effective to enhance the performance stability of a fuel cell. The use of silicone oil is the cathode catalyst layer not only improve air accessibility, it likely enhances the oxygen solubility and hence the cell performance. In this project, we have developed a 3 to 5 kW fuel cell stack incorporating the invention and know-how we have developed earlier. The stack with this power capacity is ideal for lab development before it can be used on board of a ship. The success of demonstrating this 3 to 5 kW fuel cell stack in terms of enhanced performance and stability allowed us to build a much larger power capacity stack to meet a particular need on board of a ship.

Figure 26 The development process of in-house developed fuel cell system
**Project 4: Solid oxide electrolyser cell (SOEC)**

Over the past decades, understanding of the profound implications of anthropogenic-driven climate change has grown, which is centrally around the carbon issue. This, in turn, has fueled research into options to mitigate likely impacts. Approaches involving the capture of CO$_2$ and its storage in geological formations and ocean, or even reacting naturally occurring Mg and Ca containing minerals with CO$_2$ to form carbonates as mineral storage, and subsequently used for cement production, have generated a raft of proposed solutions. While storing CO$_2$ by different means is of paramount importance as anthropogenic CO$_2$ has exceeded the amount sequestered naturally in biomass, oceans, and other sinks, it is far beyond the reach of Singapore for it being a very small nation. Thus, efforts such as diverting the energy route to hydrogen, concentrating CO$_2$ to a point source, and converting CO$_2$ to useful material feedstock in reducing the overall carbon footprint would be applicable to Singapore.

Production of syngas from CO$_2$ and H$_2$O through electrochemical means is one of the most practical solutions in reducing CO$_2$ emission. From the thermodynamics perspective, this method warrants high conversion efficiency compared to the thermochemical method. The syngas can be further synthesized to synthetic natural gas (actually methane) using the Fischer-Tropsch method. Thus, it needs little additional investments because the existing infrastructure (storing and dispensing) of the natural gas is readily available.

The solid oxide electrolyser cell (SOEC), is a promising technology for cost-competitive production of syngas, as shown in Figure 27. Driven by an external DC power source, oxygen ions (O$_2^-$) are pumped from the negative electrode side (typically Ni-yttria stabilised zirconia (YSZ) cermet) to the positive electrode side (typically lanthanum strontium manganite (LSM)-YSZ cermet) through the solid electrolyte (typically YSZ). CO$_2$ and H$_2$O are both reduced at the negative electrode forming syngas; while O$_2$ is generated from the positive electrode, which adds to the atmospheric air forming O2-rich air.

Assuming that the flow rate of CO$_2$ entering the SOEC is same as the flow rate of air, and 1 mole of CO$_2$ and 1 mole of steam would produce 1 mole of O$_2$ in the SOEC, thus the concentration of O$_2$ in atmospheric air at the positive electrode side will increase from 21% to 60.5% after passing through the SOEC. The O$_2$-rich air is very useful for enhancing the efficiency of any combustion processes. In addition, the electrochemical efficiency of H$_2$ and CO cogeneration could exceed 95%. The total system efficiency can be as high as 65% to 70%, provided that the heat is well recuperated.

While the SOEC has great potentials, there are a number of technical challenges to overcome in SOEC technology. For example, the SOEC suffers from relatively poor electrode activity, sulfur poisoning, high degradation rate, and has short lifespan. Both Ni-YSZ and LSM-YSZ, which are good electrode materials for the solid oxide fuel cells (SOFC), exhibit inferior performance when exposed to SOEC operating conditions. Ni-YSZ is known to be even poisoned by ppb level of H2S, rendering it rather vulnerable for practical application; while LSM-YSZ suffers from the problem of delamination after prolonged operation. This project to design, develop and synthesize new materials for a durable and robust solid oxide electrolyser cell (SOEC) operating at 800oC with key emphasis on solving issues, such as poor electrode activity, delamination of electrode from the solid electrolyte, sulphur poisoning, cell degradation, etc.
Project 5: Power generation in chlor-alkali plants using hydrogen fuel cells

In the fuel cell industry, where the availability of hydrogen source is often the direst issue, large quantity of high purity hydrogen is vented into the atmosphere by the chlor-alkali plants. The marriage of fuel cell to chlor-alkali plants could be said to be a match made in heaven. The electricity generated from fuel cells using the by-product hydrogen could substantially reduce electricity demand of a chlor-alkali plant. A modern membrane electrolysis plant consumes on average 3.4 MWh of electricity for each ton of chlorine produced. Electrochemical conversion of the by-product hydrogen would yield around 0.5 MWh of electricity per ton of chlorine produced, which is ~15% of the plant’s electricity consumption. This leads to a reduction in CO₂ emissions by 225 kg for each ton of chlorine produced (assuming natural gas with 50 MJ/kg LHV is used to produce 0.5 MWh of electricity through a conventional power plant with an average efficiency of 44%, i.e., Singapore’s average efficiency of power plants).

Recent studies have examined the adverse effects of chloride, specifically to polymer electrolyte membrane fuel cells (PEMFCs). The effects of Cl₂ on PEMFCs performance and durability were studied by separately injecting various HCl concentrations into the fuel stream and the air stream. When Cl⁻ was present in either the fuel stream or the air stream, the cell performance measured by cell voltage at a constant current density was characterised by an initial sudden decline, followed by a steady-state drop. The severity of the contamination effect was found to be independent of the injection side but to increase with both current density and HCl concentration. Studies also revealed that cell performance was non-recoverable in some cases, such as, with high Cl⁻ concentrations.

The team exploited the availability of the by-product hydrogen from chlor-alkali plant by using alkaline fuel cell technology. Alkaline fuel cell (AFC) is known to be the most mature fuel cell technology. A typical AFC will have an electrical efficiency of ~50% compared to PEMFC, which has ~40%. However, studies on the adverse effects of chloride and other impurities from the chlor-alkaline plant have to be performed on AFC. In this project, we performed studies to understand the poisoning behaviour of chloride ions, and with this knowledge, developed an efficient, cost effective compact and fast response gas purification system to mitigate the effects of impurities in the hydrogen feed. The desired outcome is to develop a fuel cell system that is tolerable to different impurities in the by-product hydrogen, especially the chloride ions, in the chemical industry, such as the chlor-alkaline industry.
The exploitation of renewable energy resources, the advancement of grid systems and the deployment of energy efficient technologies are urgently needed to mitigate impacts of climate change. This Programme conducts research and development of power electronic hardware, firmware and software solutions to achieve the reliable grid system integration of renewables. These include converters and inverters using the latest power devices and topologies coupled with Information & Communication Technologies (ICT). Microgrids are weak systems due to the inclusion of lower inertias of smaller rotating generators and their lower power capacity. Frequent change in source generation or load consumption will result in significant system disturbance. An Energy Management System (EMS) which is dedicated to the operation and control optimisation of microgrids where the effective integration of renewable sources such as photovoltaic (PV) and wind with energy storage (batteries, flywheel and compressed gas) is one of the main focus areas of research. The integration of storage solutions is key to mitigating intermittency associated grid instability. Besides land-based microgrids, integration of off-shore wind turbine power plants to enhance system efficiency and stability using HVDC transmission is being studied.

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With increasing penetration of DC-inherent energy sources (PV), energy storages (battery, Supercapacitor, flow battery, etc.) and loads (electronic loads and motors with variable speed drives), a combined DC grid and the conventional AC grid can help to minimize electrical energy loss due AC/DC/AC power conversions. The focus of Hybrid AC/DC microgrids includes development of microgrid components such as converters and inverters and the investigation of different coordination control techniques to regulate the voltage/frequency and voltage of the AC grid and DC grid respectively. Wide bandgap semiconductor, converter control algorithm incorporating digital signal processor (DSP) and multi-objective optimization algorithm are researched to ensure compact and high efficiency converters. Ongoing research includes development of power electronic converters using SiC for adaptive integrated hybrid AC/DC micro power parks system, and development of embedded systems with DSP firmware for converter control in hybrid AC/DC microgrids.

Intermittency of renewables is a major challenge that prevents renewable energy powered plants to meet grid compliance at a given point of common coupling. Scope of the second research thrust is therefore the integration of multiple energy resources with energy storage and safely meeting the power or real time energy demand. RD&D efforts also include the energy management system (EMS) and functions comprising source/load forecasting, optimum power flow, state estimation, unit commitment, economic dispatch, etc. and are related advanced control algorithms like Mode Predictive Control (MPC), Sliding Control (SC), Artificial Neural Network (ANN), and Machine Learning.

System stability is a major issue with weak grid system which is due to the low inertias of small rotating generators and their corresponding lower power capacities found in wind farm microgrids. The scope of DC Transmission and Weak Grids research is to find solutions such as the use of HVDC transmission to link up wind farms to enhance the stability of weak grids.

HVDC transmission has been deployed to link weak AC grids or as an alternative transmission medium to AC to reduce transmission losses. With the recent advancement in high power and high frequency power semiconductor devices and the development of high power and efficient switch mode power conversion methodologies, MVDC, HVDC and DC transmission in general has become technically and economically feasible.
Project 1: Portable, Modular Hybrid AC/DC Microgrids System

Power outages following natural disasters can be minimized and even prevented with smarter use of modern technology such as microgrids. This, however, entails massive infrastructure investment and it takes time to install such technology. Such technology is yet in its infancy and there is insufficient field experience, although a lot of research has been done over the years. Currently, emergency power supplies such as diesel generators (DGs) are deployed in the event of a disaster. This leads to the problem of diesel fuel supply as disaster areas could be totally cut off from the rest of the world. To address this shortcoming, portable modular microgrids with integrated renewable energy and battery storage would be an ideal solution for such unforeseen events. The portability and modularity of the microgrid ensures fast deployment and ease of operation during emergencies.

Portable modular microgrids could also be used to provide power for military applications and provide electricity to off-grid communities living in remote villages and islands.

AC microgrid. The modular microgrid concept allows the chaining of the modules to form a micro power park (MPP). This concept also provides significant flexibility in scaling up to a large constellation of microgrid systems that can be set up and grow organically in remote places without a strong grid. The scope covers the following:

- Advanced coordination control techniques for the MPP system.
- Bidirectional power converters, inverters, battery charge/discharge controllers, variable speed diesel generator controller, and micro-turbine controller to be integrated in a smart hybrid dc-ac grid module with plug-n-play capability, protection and isolation for quick deployment.
- Communication networks for intra-microgrid module and inter-microgrid modules in the micro power parks.
- Energy Management System (EMS) for the adaptive hybrid grid module and a Universal Energy Management System (UEMS) to monitor and control the MPP.

Key accomplishments:

- Designed and developed power electronic converters based on the SiC switching devices; converters switching frequency up to 100 kHz to reduce passive component size
- Firmware for control of PV/battery converter and bidirectional interlinking converter (BIC) implemented to realize design function.
- Resource manager coupled with the communication system to manage the microgrid module.

This project put together the advantages of AC microgrid and DC microgrid to form a hybrid AC/DC microgrid. Hybrid AC/DC microgrid is more energy efficient as it minimizes the multiple DC/AC/DC/AC conversions in

Figure 29 Micro Power Parks System Concepts.

Figure 30 Layout of the microgrid module prototype.
Project 2: Smart Field Microgrid Systems

Presently, mobile military command post carries a diesel generator (DG) set to power all its electrical equipment. A typical field deployment involves up to four command posts where each of these posts houses its own DG. Running all the DGs under partial load is inefficient and hence reduces the operational duration. DGs are noisy equipment and prevent the army from operating in silent mode which may be necessary in certain circumstances.

Smart Field Microgrid (SFM) system uses power electronics to link up all the DGs to form a common ring network to provide power to all the command posts. The power network configuration allows the power from the DGs to be shared by all the loads. With the power network, the load conditions can be matched with the source allowing DGs to be turned off under light load conditions, hence saving fuel. With SFM system, battery storage can be integrated allowing silence mode operation in addition to the enhanced power resilience and the inherent redundancies of the power network. The SFM system is able to save up to 10% diesel fuel as compared with the current system.

The focus and scope of this project entails the development of converters and inverters with an efficiency greater than 95% integrated with Li-ion battery storage and a smart controller to form one segment. Four segments are combined to form the power network as shown in Figure 31.

Key Accomplishments:

- Fully integrated and tested 4 sets of 20 kW power converters with efficiency of 97.6% and 97.8% for the rectifier and inverters respectively that have 55% reduction in size and 45% in weight compared to the best in class commercial products. Original specifications and final achievements of the converter and inverter are shown in Figures 32.
- Developed an adaptive control algorithm which allows one segment to operate in stand-alone or parallel mode where it needs to synchronize, interconnect, and share power with other segments.
- Development of an Energy Management System (EMS) to manage the whole SFM system, coordinate and control to turn-on and –off one or more segments to balance load power demand.
- Productization of the SFM system is being planned, and the first product is expected to be launched in 18 months.

![Figure 31 Schematic diagram of AC ring connection](image)

![Figure 32 SFM System: Converter and Inverter Specifications and Status](image)
Project 3: Integration of Weak Grid and Wind Turbines

1. Power Plant Controls for Weak Grid Markets
   The effect on power quality due to wind turbines on grid network is becoming an important issue due to the rapid increase of wind power penetration especially in weak grid regions. Therefore, research focus should be put on offering improved control strategies for the power converters in the wind turbine systems. This project aims to enhance wind energy feasibility in weak grid regions.

   This project involves literature review, market studies, simulations (in PSCAD & Simulink) and research reports related to the feasibility of wind turbine generator integration in weak grids. Emphasis is put on the design of a weak grid model, grid impedance estimation & compensation for variation, supporting WTG (wind turbine generator) at weak grid connection using a synchronous condenser, protection of weak grid, control and stability analysis of power converters in weak grid connection for LVRT capabilities and PLL synchronization.

2. DC Power Transmission for Offshore Wind Power Plant
   This project aims to develop a Monolithic High Power Medium Frequency Transformer for 10MW rated converter for their new potential wind plants and deliver an all-in-one computerized analysis tool which allows study of various designs and their predicted performance. Extensive mathematical models will be derived for depicting the electromagnetic and thermal behaviour. As the frequency is scaled up to medium frequency levels, there occurs various technical challenges in terms of accurate loss mechanism modelling methodologies attributed to skin and proximity effect as well as predicting the hot spots and temperature rise of the transformer arising from multiple material type interfaces that vary widely as function of core, windings, insulation and heat sink types. Experimental validation of the design method will be demonstrated at different high power levels. At present, based on the research carried out, there is not such all-inclusive tool that is commercially available which can accurately predict the above mentioned aspects.

   The key focus area of this project includes review of start-of-art medium frequency high power transformer design methodologies, analytical tool GUI development and SRC simulation interface development. 10kW prototype transformer development using, FEM of the transformer design. Based on optimization routines from FEM and the 10 kW inputs, a 100 kW transformer will be designed and built to verify the methodology used in the transformer design tool. The second focus area is modelling and simulation of field excitation control of would rotor synchronous generator with DVR voltage regulator.

   Figure 33 Weak grid solutions

   Key Accomplishments:
   • Development of a Weak Grid Model that defines a typical topology where wind power is connected and its classification with different indexes, generation type and loads.
   • Analysis of state-of-the-art grid impedance estimation techniques and compensation for variation in grid impedance. Technical report documenting the market scan and classification for synchronous condensers. Simulation of Synchronous Condenser for providing support to WPP (Wind Power Plant) at weak grid connection. Technical report documenting the state-of-the-art weak grid protection system for use at substation and collector system.
   • Simulation models and reports pertaining to analysis of converter control in weak grid setups with focus on grid current control, synchronizing to the grid with a phase locked loop setup, active and reactive power control and exposing combined control to external disturbances.

   Figure 34 Wind Power Collection in Offshore Windfarms

   Key Accomplishments:
   • Completed design requirement specifications and computer tool requirement specifications for medium frequency, high voltage transformer design. Completed state-of-the-art report for high voltage medium frequency transformer. Completed software flow-chart for transformer core design, winding layout design, transformer single-run design, and design for optimized volume/efficiency. Completed main interactive GUI with sub-menus to support user input and design output and defined import/export interface with FEM simulation and Simplore/PLECS circuit simulation. Completed sub-GUI design for the design of magnetic core design, wiresize, insulation and winding layout with their
• Completed wound rotor synchronous generator excitation control modelling with passive rectifier and working on DVR control modelling and simulation.

3. Wind Turbine Efficiency Enhancement

The industry is interested in an ever more detailed time-stepping simulation model of their power converter system, and would be interested in conducting Plecs/Matlab control simulation of the new full scale converter. This will allow more precise and detailed system and component simulations. The outcome of the modelling and simulation results with Plecs/Matlab will enable running simulations using different operation scenarios to study converter performance in terms of voltages, currents, thermal etc.

The key focus areas for this project is to establish a simulation system to run MSC/SLC controller with Plecs circuit components with detailed transient circuit modelling of the permanent magnet generator, induction generator, all circuit component of modular converter with/without PWM modulation. The normal PWM vs. random PWM modulation, encoder fault, grid fault circuit model needs to be built to allow the simulation to run at different converter operation scenarios. Plecs thermal models for major power components including IGBT, inductor, and transformer for converter control system needs to be developed to evaluate the modular converter thermal performance. User friendly simulation GUI design for circuit component variation with automatic simulation report generation for multiple simulation runs is another area of focus of this project.

Completed PM machine model modification for converter system simulation to support generator power and speed reference setting changes. Completed generator side converter control and grid side converter control and tested power ramping, up and down with speed changes. Working on integrating of converter control system with circuit models.

Figure 35 IGBT based 10 MW interleaved converter topology.
Project 4: Integration of 100 kWh Vanadium Redox Flow Battery at CleanTech One (CTO) building

The intermittent nature of solar energy resource needs energy storage system for storing, stabilizing and regulating energy for building level grid integration. The challenges include operation in hot and humid tropical climate conditions, space constraints, safety, and lifetime replacement of the energy storage system. Vanadium Redox Flow Battery (VRFB) is one of the promising candidates for large-scale energy storage, particularly suitable for energy generated from renewable sources such as solar photovoltaic systems or wind power plant.

Commercial scale VRFB installations for renewable energy storage in Europe and the USA have been reported. However, this project represents first of its kind installation in Singapore. The operation and long-term performance of the VRFB in tropical climate conditions, and integration and testing of VRFB with solar PV and loads at a localized building power grid is investigated in this project.

After installation, VRFB was connected to solar PV installation on the roof-top of CTO with 8 kWp of solar PV power supply. It was then connected to electrical loads at the labs of ERI@N and electric vehicle charge station for testing the performance with different types of loads and conditions. Schematic diagram of integration is shown in Figure 36.

The objectives of this project include:
1. Testing long-term charge/discharge cycles performance of large scale VRFB in tropical climate conditions
2. Pilot scale testing of VRFB integration with solar PV and loads in building level microgrid in island mode operation, intermittency management, and grid mode arbitrage application, etc.
3. Testing of additives (developed by the Energy Storage team @ ERI@N) for improving thermal stability of electrolyte

The integrated system is being tested in off-grid island mode. Preliminary performance test results of Cellcube with solar PV and lighting load are shown in Figure 37. The initial results show stable grid output to the load despite fluctuation and intermittency of solar PV output during cloudy and rainy days. The VRFB absorbs the fluctuation of solar PV output. Excess power during sunny days goes into charging the Cellcube unit. Energy stored is discharged to the load during cloudy and rainy days, and low sun hours. The electrolyte temperature maintains around 320 to 350 °C and does not significantly affect the thermal stability of electrolyte.

Figure 36 Integration of Cellcube FB10-100 VRFB with solar PV and loads for island mode operation pilot tests at CleanTech One (CTO) building.

Figure 37 Preliminary performance test results of Cellcube VRFB with solar PV and lighting load.
**MULTI-ENERGY SYSTEMS AND GRIDS**

To develop cost-competitive solutions to improve its energy efficiency, reduce carbon emissions, and broaden its energy options, Singapore has embarked on an energy transition which includes increased focus on natural gas and LNG and on deployment of at least 350 MW of solar energy by 2020. Introduction of renewables and distributed generation will need a revamp of Singapore’s grid system into an interoperable network, leveraging two-ways flows of energy and communication. The next generation grid that will leverage on solid state transformers will be a digital grid that will also allow Singapore to maintain grid resilience to counter new load and source dynamics in the distribution networks. Another key factor to be considered is, although smart grids have been studied extensively in the recent years, grids which are emerging in many industries and districts are Multi-Energy Grids, which need optimization of not just electricity, but also thermal energy (both heat and cold) as well as gas/chemical energy. Thus, this programme focuses on the next generation grids, being next generation electric grids and also next generation multi-energy grids and multi-energy systems.

### Programme at a glance

<table>
<thead>
<tr>
<th>Established</th>
<th>2016</th>
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<tr>
<td>TRL targeted</td>
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</tr>
<tr>
<td>Research staff</td>
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</tr>
<tr>
<td>PhD students</td>
<td>8</td>
</tr>
<tr>
<td>Participating Professors</td>
<td>A Romagnoli, P Wang, Y Tang, H Yu, J Luo, S Sundaram, D Niyato, J Lai</td>
</tr>
<tr>
<td>Laboratories</td>
<td>Hybrid AC-DC LAB@CIT, Heat Transfer lab @MAE, WER@EEE</td>
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Power electronic conversion systems based on novel power topologies have made huge advances using wide band gap semiconductors devices like Silicon Carbide (SiC) and Gallium Nitride (GaN) compared with IGBTs and MOSFETs. They are more rugged, can operate at high temperature and with very high-frequency magnetic isolation in the MHz range. While global efforts continue to push designs at higher power density and higher switching frequencies, the reliability of such power dense converters tend to pose bigger challenges along with EMI/EMC issues and heat removal. The main focus areas of thrust would be to realize sub-systems based on wide-band gap devices, advanced packaging, and thermal management methodologies for high density/power conversion systems; supported with capability to accurately assess magnetic losses and semiconductor reliability using advanced modelling and Finite Element Analysis (FEA).

Existing grids based on line frequency transformers with proven reliability have reached their performance limits due to the harmonic distortion and electromagnetic interference, emanating from integration of renewables and battery storage controlled by power converters. They also are subjected to transient voltage variations and random power output caused by the intermittencies of PV and wind power. Worldwide efforts are underway to create grids that are more resilient and self-healing, by integrating grid-scaled energy storage and smart grid technologies to optimise the use of existing electricity transmission and distribution infrastructure. These are at developmental stages, and are yet to be deployed in the power distribution networks. The three main focus areas of research are the development of Solid State Transformers (SSTs) as building blocks for the next generation grid; the design of scalable architecture to integrate SSTs in existing grid system with renewables and energy storage to maximise efficiency and reliability; and to enable energy routing between SSTs to optimise cost in Grid 2.0, the next generation Smart Grid.

In most industrial estates and large campuses, energy generation and end-use entails electricity, thermal, and gas networks. While substantial efforts have been invested in smart grids for electric networks, management and optimization of multi-energy systems is essential for addressing energy efficiency at industrial sites and sites that invest significantly on distributed generation. Main areas of focus in this thrust include optimization of polygeneration and waste heat recovery, energy storage (thermal, gas, and electric), monitoring and control systems, interoperability of software/hardware, and integrated management of multi-energy systems.

### RD&D Focus

**Advanced Power Electronics**
- Wide bandgap devices
- Compact power converters and high frequency, high temperature switching
- Protection devices for DC distribution

**Next Generation Grids**
- Novel distribution architectures and digitalized power systems technologies
- Design for multi-functional & power dense equipment
- Solid State Transformers
- AC/DC grids

**Multi-Energy Systems and Energy Management**
- Multi-Energy-system - interoperability
- Polygeneration, thermal storage and grid integration
- Energy forecasting and prediction
- Management (DRM) and Time of Use (TOU) pricing
Project 1: Thermal Energy Systems for Multi-Energy Grids

In an industrial setting, addressing electricity alone for energy cost reduction and efficiency is inadequate. Industries need oil, gas, steam, and process heating and cooling and represent major contributions to energy consumption, GHG emissions and local pollution. Energy sources of electricity, heat, and gas co-exist from an operational viewpoint, with these vectors being deployed in combined heat & power generation (CHP), tri-generation (electricity, heating, & cooling), air-conditioning & heat pumps. A polygeneration power plant is seen to have a significant opportunity to increase the performance (power and efficiency) and consequently to reduce the primary energy source consumption.

The research activity in this direction has been encompassing several aspects related with polygeneration with particular focus on thermal energy recovery and management. The former has been investigated by looking into optimization, design and analysis of thermoelectric generators (TEG) and closed power cycles (Organic Rankine Cycles - ORCs).

Thermoelectric generation is one of the main drawbacks limiting a wide deployment of TEG systems comes from the poor performance of the thermoelectric materials (with figure of merit, Z < 1); although a significant amount of research has been focused on improving the thermoelectric properties of the materials to be adopted in TEG systems, another opportunity is also offered by the system integration and control of TEG systems. Preliminary test results carried out by Thermal Energy Systems group showed that for a given TEG module the interface material (either thermal pads or commercial thermal grease, etc.) significantly limits the max power output (from ≈10W down to ≈3.84W). Based on these results the team is currently looking into novel manufacturing techniques for TEG systems (e.g. liquid forging, diffusion bonding or nanosystems). Indeed, reducing the number of interface materials (each one holding different thermal conductivities) and components could lead to an overall TEG improvement in terms of power output, weight, lifetime and costs.

Closed power cycles (Organic Rankine Cycle) - waste heat sources inherently exhibit a fluctuating nature, the characteristics of which will be dictated by the process from which the waste heat is coming from (e.g. batch processes in industrial processes, fast pulses in internal combustion engines, etc.). Fluctuations can include both thermal power (e.g. mass flow of a hot exhaust gas) and temperature of the source.

In order to evaluate the dynamic behaviour of the ORC subject to a periodically fluctuating heat source, a characteristic behavior of the response time of the evaporator is currently being investigated. The characteristic response times can be tabulated for different geometries and materials of heat exchangers as well as flow properties and regimes in order to give a general map of expected characteristic response times plotted against relevant parameters. These timings can then be compared to the expected or observed periods of fluctuation on the waste heat source in order to predict in which of the dynamic regimes the ORC will operate.

The output from the analysis showed that it is possible to generate dynamic response maps for the evaporators which could then be used for optimizing the control of the ORC systems. Based on three non-dimensional parameters describing the geometry, fluid thermal state and wall material, ‘bubble maps’ can be generated and compared in order to capture the impact of each parameter on the dynamic response of the evaporator. The next activity of this research is that of identifying a typical case study (e.g. flue gas from heavy duty engines) and develop a control algorithm using the bubble maps as look-up table. The team is currently collaborating with several companies as well as academic institutions to assess and validate the proposed methodology and assess the improvement (in performance) which could come from an optimized control strategy.

### Thermal analysis

<table>
<thead>
<tr>
<th>Thermal conductivity (W/mK)</th>
<th>Thermal material 1</th>
<th>Thermal material 2</th>
<th>Thermal material 3</th>
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<tbody>
<tr>
<td></td>
<td>5</td>
<td>8.5</td>
<td>8.5</td>
</tr>
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</table>

Max output Power & V-power graph

- $P_{\text{max}} = 3.84 \text{ W}$
- $P_{\text{max}} = 5.66 \text{ W}$
- $P_{\text{max}} = 10 \text{ W}$

Figure 38 Thermal Management Challenges for TEG

Figure 39 Representation of different thermal power regimes
Project 2: Multi-Energy Management and Information System

In a typical industrial estate (e.g. petrochemicals, pharmaceuticals, semiconductors, ports), in addition to the grid supply, local electricity/steam generation is accomplished with oil and gas and the total losses including co-generation (co-gen), transmission & distribution, process end-use losses can be as high as 64% with 23-32% losses from co-gen.

Apart from direct energy losses, there is also a huge untapped cost and energy saving potential due to decoupled energy networks (viz. gas, cooling, electric networks), inefficient integration of distributed generation, and energy storage facilities, and lack of interoperability of operating systems such as data monitoring and automation tools. This results in over capacity, underutilization, lost opportunity costs and sub-optimal performance on the energy and environment front. Further opportunities to interact with the electricity market via demand response and benefit from dynamic market pricing are also limited due to the unavailability of an effective data-driven integration tool.

The key focus of the SMES is to achieve substantial energy (at least 20%) and cost savings (at least 30%) resulting in at least 20% carbon emission reduction, in multi-use sites, through optimum use of multi-energy sources while enhancing energy mix management and network resilience on a smart microgrid backbone.

This project aims to develop a software enabling system level optimisation using operational assets for validation of the software’s capabilities. This software should be designed on a scalable platform; interoperable and compatible with multi-vendor and client user hardware and software systems, supported by an intelligent data management system that feeds into robust data analytic engines to optimise energy usage and realise cost savings.

The microgrid is the backbone structure for transmission of power in the district, hence, to achieve stability and reliability with respect to the ecosystem of technologies it interlinks with, it must require intelligent control. Solar systems coupled with right sized storage systems i.e., thermal and electrical, is key to mitigate impact of intermittency both with cost and operational effectiveness. This is strengthened by enhanced real time monitoring and forecasting i.e., solar and weather forecasting, to predict or react to rapid system fluctuations e.g., frequency and voltage. A system load forecasting capability is also critical for right sizing of baseload and peak requirements from DERs and cooling systems, it would entail consolidating building load data using an integrated BMS to achieve not only central monitoring but also central control to balance power supply and demand. Excess power from Solar system can also be redirected into storage system to be released later on, based on specific requirements. This demand side system level integration and optimisation requires a combination of smart grid technologies with functionalities enabled by an intelligent interoperable software.
Project 3: Design of Next Generation Distribution Grid 2.0 For Singapore Using Solid State Transformers for Grid (SSTG2)

This project funded by National Research Foundation (NRF) aims to develop the critical building block, the solid state transformer (SST) at 6.6kV, 50 kVA, for the Grid 2.0, the envisaged next generation grid for Singapore. This will be scaled to 22 kV, 10 MVA SST in phase 2 of Gate 1 in the programme schedule. The core components of the technology include the Silicon Carbide (SiC) based MOSFETs and high frequency isolation transformer, both of which will be extensively characterised for the design purpose to meet the stringent requirements of power utility companies. As the efficiency and reliability requirements must meet the present SAIDI and SAIFI targets, and also enable seamless integration of solar photo-voltaic in the grid, the challenges are immense in terms of both design techniques, including high frequency PCB layouts, EMI/EMC mitigation, electrical insulation, Gate-drive design to mitigate oscillations and reduce switching loss, resonant power conversion circuit topologies for high efficiency, co-ordinated fault handling, monitoring and control. Verification and experimental validation have been planned to target the initial simulation results which will be exhaustively performed. At present, based on the detailed market and literature survey conducted, there is no commercially available SST in the market that can be directly installed with the required characteristics mentioned above and hence, none has been deployed in the distribution grid in the global scenario.

The key focus area of this project includes a review of the state-of-the-art SST development methodology, analytical simulation for SST and integration to grid including PV load, AC/DC rectifier, Dual Active Bridge (DAB), DC/AC inverter simulation with multiple type loads as in Figure 42. Hardware development of a 50 kVA SST prototype, reliability model and test, experimental verifications at EPGC and modular design for scale up to 22 kV and 10 MVA is planned as in Figure 43. The 50 kVA SST simulation model will be verified and validated. The 2nd focus area of this project is to verify the multi-functionality of the SST including integration of renewables and battery storage; active power factor correction, static VAR Compensation, and energy routing possibility Grid 2.0.

Key Accomplishments

- Completed design requirement analysis and the project proposal include the topology architecture planned to be studied shown in Figure 44. A detailed literature survey was completed and various topologies were compared with respect to their performance. Completed initial interaction with key industry collaborators and research agreements with clear objectives have been defined.
- Completed detailed design plan with critical work packages planned to evaluate, characterise, verify and validate the design.
- Completed initial version of medium frequency transformer design based on DC losses mechanisms are embed in a tool for the development of high-frequency transformer design that will be a critical part of the SST.

Figure 43 Deployment plan at the distribution scale

Figure 44 SST topology
The power control of turbines is required for good precision, hence, it requires quite accurate current and voltage transducers. Besides the requirement to the sensors, it has turned out that for large turbines where the grid current is in the range of several kA, the designer has to be careful with the conductor shape through the sensor, the sensor layout itself, as well as the distance from a sensor to neighbouring conductors and from sensor to sensor. The issue is believed to be related to local saturation of the current sensor core. Figure 45 shows an example on the current harmonic where the second plot represents the centre phase. Clearly, the third harmonic component is much more pronounced in this phase. The project aims to provide a design guideline based on the analysis of CT to measure 6000 Amps of switching current.

### Project 4: Design of Electromagnetic Transducers

The power control of turbines is required for good precision, hence, it requires quite accurate current and voltage transducers. Besides the requirement to the sensors, it has turned out that for large turbines where the grid current is in the range of several kA, the designer has to be careful with the conductor shape through the sensor, the sensor layout itself, as well as the distance from a sensor to neighbouring conductors and from sensor to sensor. The issue is believed to be related to local saturation of the current sensor core. Figure 45 shows an example on the current harmonic where the second plot represents the centre phase. Clearly, the third harmonic component is much more pronounced in this phase. The project aims to provide a design guideline for the use of high current sensors.

- Preferably, the guideline should include (but not limited to):
  a) Some guidance on when and how the phenomena occur (all aspects causing the phenomena to occur should be explored and explained).
  b) Guidance on conductor shape (when can squared bus bars be used – preferred because they are cheaper)
  c) Guidance on conductor distance to sensor (both the conductor that is passing through the sensor and the conductors belonging to the other phases).

### Key Accomplishments

At the present, no considerable accomplishments were obtained. The major deliverables are summarized below:

1. FEM analysis could reflect magnetic saturation, while it does not replicate the exact current distortion found in real case.
2. The trend has been found - magnetic flux density is more pronounced in centre phase compared to other two phases.
3. Single phase studies focused on investigating the influence of the position and shape of primary bus bar, as well as the core material properties. The results show that measurement error is highly dependent of core material, where modest eccentricity could result in significant error.
4. The generalized three phase current measurement guideline completed for future CT designs will be used to measure currents in the range of 6000 Amperes, to ensure high accuracy current measurement.
5. Parallel allocation of CTs and bus bars proposed when space is not a concern.
6. Idea proposed to place centre bus bar and CT in orthogonal with side bus bars and proved in FEM analysis.

### Significance and Scope

- Create FEM models to be able to reproduce the current sensor distortion phenomena.
- Based on the FEM models to be able to write a design guideline for the use of high current sensors.
This project is for high rating switching power converters in the 10 MW design range. For the industrial partners, a number of smaller units are often connected in parallel to achieve the power rating required. When paralleling converter sections, they are often controlled as one, meaning that the same control signals are distributed to the different sections. Figure 46 shows a simple representation of parallel converter branches, with sources representing the converter branches, and on the right a voltage source representing the grid. In front of that source is a filter to refine the switching harmonics from the converter branches. The resulting harmonics determines the requirements for the filter. If the switching instances of the different converter branches can be misaligned, the current ripples of the different converter systems will be added together, but peaks of the ripple will not coincide with each other. This principle is illustrated on the right of Figure 46, where it can be seen that the peak of the total ripple has been lowered and averaged out.

Figure 46 Preliminary performance test results of Cellcube VRFB with solar PV and lighting load.

Significance and Scope
1. Generic electrical simulation model: to establish a simulation model in Plecs with two to five grids connected, converters using same DC-link as well as the same grid connection.
2. Different modulation schemes need to be pre-defined and easy to change
3. Current and voltage loading on individual components, as well as their losses, have to be output of the model (of post processing of data). Details on loss modelling, e.g. magnetic elements, need to be discussed as project progresses.
4. Converter design with the aim of complying with harmonic standards: to analyze converters with interleaved switching that fulfils the harmonic standard. To study how variation of certain design variables affects other design variables. The design variables to consider should include (but not limited to): PWM scheme, grid inductor, switching frequency, interleaved angle, common mode inductor, filter capacitors, number of parallel converter units.
5. Inductor design: the purpose is to come up with different inductor lay outs and be able to provide a qualified picture of the inductor weight, volume, losses and price.

Key Accomplishments
At the moment, there are no obtained accomplishments. The major deliverables are summarized below
1. Based on simulation it was proved that the performance (harmonics) of the DPWM3 is worse than the other DPWMs for grid connection application. Traditionally DPWM3 is considered as being superior to other DPWM in terms of waveform quality, but this conclusion is drawn from using inductor filter (L filter). When LCL filter used, or D/Y transformer is used for grid application, the results may differ.
2. The line inductance $L_f$ is limited by the harmonic level. In the current project, the minimum line inductance is determined by the ripple level without considering the modulation scheme. The relationship between the minimum line inductance and system parameters such as modulation schemes, dc-link voltage, and switching frequency etc. should be studied quantitatively.
3. Multiple inductor types were designed and the performance of different inductor designs were compared regarding to the total losses, weight and size. For example, two inductors based on CI and integrated concept can be designed with the same core size, and the losses and harmonics can be compared analytically or from simulation, which can verify the effectiveness of the integrated concept.
According to a recent United Nations Environment programme (UNEP) report, buildings use around 40% of global energy and this sector is the largest contributor to global GHG emissions. Additionally, energy consumption of building sector is rising rapidly due to increasing population and higher economic activity in most parts of the world. In Singapore, according to EMA report on energy consumption released in 2015, the energy consumption for non-residential and residential buildings consume about 50% of the electricity production. It is, therefore, essential to focus on energy efficiency in this sector through technologies that can significantly improve the energy efficiency of the buildings, while ensuring optimal liveability and long term sustainability. The SSBT programme focuses on research, development and demonstration of innovative, energy efficient and cost effective solutions.

Modelling and simulation of building performance via the use of computational tools and techniques can ensure a more scientific and informed method of adopting optimal technologies that are relevant to designing appropriate building elements and deriving maximum benefits from their synergies in a cost effective way. The simulation team at SSBT focuses on integrated design, modelling, and optimization of the building envelopes and active building systems, using energy modelling tools and computational fluid dynamic simulations to accurately predict and control the buildings’ performance.

Efficient and cost-effective cooling is one of the biggest challenges for the building sector, while ensuring the optimal thermal comfort of the occupants. Apart from control strategies for cooling and mechanical ventilation, the team investigates novel cooling approaches such as desiccant based dehumidification, thermal chillers, active chilled beams, radiant cooling, air distribution and ventilation, indoor air quality, and solar thermal cooling techniques.

In order to achieve a holistic green building design, the traditional approach towards energy efficient building (mainly focused on active systems) will have to take a 360 degree turn. In context of energy consumption and emission reduction, buildings must be inherently designed to contribute towards energy efficiency through appropriate passive design strategies that can be thermal and visually optimised, providing excellent indoor air quality opportunities. These opportunities must be reinforced with innovative passive technologies to improve the building envelope and fenestration performance that can reduce the cooling load and directly contributing towards reducing the environmental impact of the building. For example, researches related to cool paint performances, windows film rejecting the heat and solutions increasing the thermal comfort inside the building are studied.

A recent addition to the SSBT focus is Smart Lighting Systems and Sensors. This newly adopted RD&D domain aims to promote, initiate and deploy energy efficiency and smart solutions for indoor and outdoor lighting systems. Such solutions focus to achieve energy savings though LED technologies and appropriate controls, while smart systems aim to offer intelligent systems with decision making capabilities, and most importantly, taking care of users’ visual comfort by offering appropriate lighting effects and services. Researches focus areas could be divided in four domains: hardware, eco-system, software control and infrastructure. Lighting aims to offer more than illumination, but also comfort, personalization, communication and services.
Environmental sustainability design for buildings is most effective when applied at the earliest stages of the design processes. This philosophy was well understood and accepted by the Office of Development and Facility Management (ODFM) at NTU, who decided to engage the SPS team under the SSBT programme at ERI@N, to assist them in designing their new lab intensive Academic Building at North Spine of NTU, to achieve above and beyond BCA’s Green Mark Platinum standard under Green Mark Incentive Scheme - Design Prototype (GMIS-DP) award, based on Green Mark Criteria for Non-Residential Buildings version 4.1.

Objectives
• To demonstrate the effectiveness of integrated design for high performance building and to explore the most energy efficient strategies/technologies for lab intensive building without compromising on safety of users to surpass Green Mark Platinum standards
• To validate systems performance through building modelling and simulations.
• To extensively measure on benchmarking lab & office plug load, and also to verify energy savings through metering actual implementation device.

Key Outcomes:
• As part of the integrated design process, SPS team has worked closely with the other building stakeholders to assess innovative technology/system performances, and verify energy savings potential through comprehensive modelling simulation to further optimize the building design
• 44.12% energy savings was achieved with the proposed strategies and technologies compared to the baseline code compliance for lab intensive buildings. This project has been awarded BCA Green Mark Platinum Award as of January 2016
• Design prototype for lab intensive building under BCA's GMIS-DP

Other SPS projects
The SPS team has collaborated with BCA and other agencies on a number of projects, including development of Building Energy Efficiency Roadmap for Singapore, SPS of JTC’s CleanTech Two and NSAB, and also test-bedding of innovative technologies and systems for

EcoCampus initiative programme, such as chilled ceiling, cool paint and smart lighting to name a few. This puts ERI@N in a very strong position to perform on-going research projects, as follows:
• Test-bedding Research for Innovative Technologies, including facades, solar-shading, HVAC, daylighting, electric lighting, and building controls. This test bed facility will feature a rotatable test bed facility to simulate an office environment for testing and benchmarking plug-and-play products and systems in the tropical urban environment.
• The significant SPS capabilities enabled this project to get funding for Ultra Low-Energy building initiative (2016-2020). This initiative focuses on developing and implementing sustainable building design strategies to create Positive-energy low-rise Schools, Zero-energy mid-rise buildings and Ultra Low-energy high-rise office (U-Lo). It’s also worth mentioning that such background will place the project in a strong position to receive the Low Carbon District (LCD) award, an initiative beginning in 2017.

ERI@N also proposed research and development of innovative building technologies and sustainable infrastructure solutions for Jurong Innovation District (JID), Singapore’s largest living lab for the testing and development of new technologies.
**Project 2: Indoor Air Quality (IAQ) improvement in Buildings**

Urban population can spend more than 90% of the time staying indoors, and the trends are well reflected in Singapore, where rapid urbanisation and economic growth have dotted the landscape with buildings. However, a variety of human symptoms (e.g., allergy, asthma and cardiovascular diseases) have been found to be associated with human exposure to indoor particulate matter (PM) and bioaerosol. In Singapore, the situation is compounded as industrial, transportation and construction activities, coupled with the annual episodes of haze smoulders the air in fine PM that penetrate indoors. Indoor bioaerosol is another source of concern, as it is responsible for the spread of infectious diseases (such as influenza, measles, tuberculosis, etc), triggering allergic reactions. They contain pathogenic and non-pathogenic fungi, bacteria, viruses, microbial toxins, pollen, etc, and their sizes span between the nano- and micro-meter ranges.

**Objectives:**

a) **Fundamental indoor PM and bioaerosol dynamics**
   This study investigates the dynamics of fine PM and bioaerosol indoors, especially the indoor/outdoor (I/O) correlation between outdoor PM & bioaerosol and IAQ. This include site monitoring and sampling of PM and bioaerosol to understand the penetration mechanisms of outdoor PM to indoor environment as well as the role played by Air-Conditioning & Mechanical Ventilation (ACMV) system in the penetration mechanisms and indoor PM removal.

   **Outcome:** Support the development of energy-efficient strategies for indoor PM and bioaerosol control in tropical climate.

b) **Energy-efficient filtration system**
   This study aims at developing a novel air filtration technology that enhance the filtration efficiency for fine PM (PM2.5) and bioaerosol without adding flow resistance (energy consumption) in the ACMV ductwork. The technology being investigated is acoustic agglomeration. Sound waves are being propagated along the ACMV air distribution ductwork to create notes where fine PM and bioaerosols will collide with each other and form larger agglomerates. These large agglomerates are easier to be caught by air filters, thus enhancing the filtration efficiency without switching to higher grade filters (higher airflow resistance).

   **Outcome:** enhancement of air filtration efficiency without adding air resistance (energy consumption) to the air distribution ductwork.

**Future research study**

**Basic research on the influence of indoor air quality on mental well-being.**

This project will establish the link between exposures to different levels of PM pollution and the cognitive health in Singaporeans. It will include a comprehensive survey of indoor air-pollutants and ventilation in typical Singapore dwellings, controlled study of associations between indoor air quality (IAQ) and different cognitive function (verbal, concentration, memory, etc.) in the long and short term, and propose measure to improve IAQ for improved cognitive health.

**Controlled chamber study**

- Blinded study: repeated measurements of cognitive function on the same individual as he/she exposed to different levels of indoor PM
- Experiments to be conducted in ERI@N/EEE ACMV Lab
- Different indoor PM levels to be controlled by fitting filters of different rating in the ACMV system
- Monitoring of PM levels: PM2.5, Ultra-fine particles
- Simultaneous monitoring of IAQ parameters (air temperature, RH, formaldehyde, VOC, CO₂, ventilation rate)
- Cognitive function to be assessed by recognized tools, e.g., Strategic Management Simulation (SMS)

**Site monitoring study**

- IAQ monitoring of campus buildings including both GreenMark certified and non GreenMark certified ones
- Monitoring of PM2.5, UFP, air temperature, RH, VOC, CO₂ ventilation rate
- Simultaneous monitoring of outdoor air quality
- Questionnaire survey on perceived air quality, sick building syndrome symptoms among occupants in both types of buildings

**Outcome:** Support the development of next generation health-based IAQ guidelines for Singapore.
Project 3: High albedo and Heat rejection coatings

A building envelope acts as a thermal barrier and plays an important role in regulating interior temperatures. It helps to determine the amount of energy required to maintain thermal comfort within the built space. By minimizing heat transfer through the building envelope, crucial energy savings can be achieved by reducing the cooling demand.

A proposal to investigate the applicability of cool paints to reducing the ambient temperature and heat-island effect across Singapore, “Cool Singapore” recently received funding as part of the EIRP programme. This is an area where ERI@N has worked previously with Lawrence Berkeley Lab and then subsequently with BCA and HDB as part of a project “SkyCool” funded by A*Star and MND. This project evolved into study of PCM based cool paints, and finally a cement based solution project under EcoCampus initiative, which was undertaken with a major industry collaborator. The project included impact study of high performance insulation material for all envelope components.


Cool coating is an emerging energy saving technology for energy efficient buildings. Cool coating provides high total solar reflectance (TSR) and thermal emittance on the applied building surfaces to reduce solar heat gain, and enhances heat loss through reflectance of thermal radiation. The surface properties (TSR and thermal emittance) are crucial to the building cooling performance of cool coating. However, building surfaces are subjected to various environmental conditions that could deteriorate surface properties of cool coatings. Development of technologies that preserves the surface properties of cool coating are essential to realise the full energy saving potential.

Enhancement of anti-soiling performance
Water wash-off experiments show that all Core Shell Nano Particles (CSNP) modified cool coatings exhibit better anti-soiling performance than original SkyCool Coating. This formulation is able to restore over 35% of its loss TSR due to soiling and was successfully developed through this exercise.

Enhancement of building cooling performance
Due to the enhanced anti-soiling performance, the CSNP-modified cool coating formulation developed in this project provides extra enhancement of building cooling performance. The numerical simulations show that a best-performance CSNP-modified cool coating provides 19% more building cooling effect than the original SkyCool coating on a typical concrete flat roof.

2. Cement Based solution

**Objectives:**

1. Thermal performance evaluation of an innovative light weight cement based material (basic testing of material properties)
2. To generate data sets based on real time monitoring of application in a live built space (hall of residence-4 on NTU campus)
3. Develop numerically models that compare the heat curbing performance of the applied material on the external envelope surfaces in tropical climatic conditions

It was observed that the material has “heat sink properties” that may be useful for future works especially in combination with phase change materials for night time cooling and reducing urban heat island effect.

**Future Plans**

A combined experience as well as the expertise developed from the above mentioned project, ensured the award of grants to start an ambitious new project “Cool Singapore”. The project was kicked off at the beginning of 2016 and it aims to reduce Singapore’s ambient temperature by 4 °C in urban areas. The project will integrate various strategies and technologies for cool paint application to achieve its goals. The project aims to carry out its research on the findings of a pilot study carried out in the US (Santamouris, Solar Energy 103 (2014) 682–703 study), which shows that there can be a drop in ambient air temperatures in urban areas if there is an increase in the urban albedo.
Project 4: Liquid desiccant dehumidification, Air-conditioning and air distribution - Active and Passive Thermosiphon Beams (ATB/PTB)

Air-conditioning is one of the biggest energy consumers in the building sector, particularly in commercial and residential buildings, accounting for up to 50% of the electricity consumption in Singapore. Liquid desiccant based air-conditioning and dehumidification (LDAC) system, using renewable energy or waste heat, is one of the most efficient cooling technology for tropics, offering several advantages: (i) it can reduce electrical energy dramatically by removing the latent load using a low grade waste heat or renewable energy, (ii) fewer moving parts, (iii) working fluid (liquid desiccant), also can perform as energy storage medium. ERI@N researchers developed and demonstrated such solution using membrane based dehumidifier, and regeneration system which could able to achieve energy savings up to 60%, as compared to conventional Air Conditioning & Mechanical Ventilation (ACMV) system. In ACMV system, mechanical ventilation shares 20% of energy cost and responsible for achieving uniform space cooling and better indoor air quality. Researchers from ERI@N and the School of Electrical and Electronic Engineering (EEE) spent several years on researching and developing air treatment and distribution system, innovating and optimizing building cooling products and services in research, consultancy, product development, and education for green cooling and air-conditioning technologies, which will benefit Singapore and other regions.

Objectives
• To improve Liquid Desiccant Air Conditioning (LDAC) performance by using hydrophobic membrane to suit Tropical Climate region,
• To develop integrated controls,
• To develop models for large scale installation,
• To commercialize the invented technologies on active/passive chilled beams systems

Air T&D products
A range of products have been introduced for various ATB and PTB applications

Future projects
1. Project team acquired several projects to implement the Active/Passive Thermosiphon Beams (ATB/ PTB) as their pilot projects.

• Demonstration at ERI@N lab at level 2: Preliminary design was done. Discussion with ODFM to incorporate into tender document.

2. Products Performance Test: a reputed product testing, inspection and certification service provider has certified the ATB and PTB units’ performances at industry environment. The testing is completed and certification was delivered in August, 2016.

Future Plans
• Demonstration project for liquid desiccant dehumidification system,
• Improve the performances of the terminals units,
• Minimize product cost,
• Market leader in air treatment and distribution technologies providing energy-efficient and better indoor environment quality ACMV solutions and services.

ECOPHIT Partnership
In 2013 SGL Carbon and ERI@N signed a Memorandum of Understanding (MOU) to study various energy efficiency measures for buildings in Singapore. The project ‘Chilled Ceiling Test Bed at CleanTech One’ was proposed to study the benefits of using SGL Group’s product (ECOPHIT), chilled ceiling panels instead of conventional air-Conditioning systems prevalent in Singapore.

The research project led by researchers from the SSBT programme at ERI@N, in collaboration with SGL Group and BARCOL Air, investigated the performance of the radiant chilled ceiling system – SGL Group’s ECOPHIT technology at ERI@N’s CleanTech One office. A team of modelling and simulation experts recreated the building space and integrate a chilled ceiling system into it using an energy modelling software.
Data from the Building Management System (BMS) was used to validate the model and the simulated results. Another identical model was created without the chilled ceiling system to measure the performance of the ECOPHIT system against a conventional Variable Air Volume (VAV) air-conditioning system.

The two models were compared and the energy consumption of each was measured. These models can be used to predict the effectiveness of future chilled ceiling installations. A study measuring the thermal comfort of occupants was also done, to ensure the feasibility of the chilled ceiling system. The results of this project are expected to provide more insights on the viability, efficiency and thermal comfort of radiant cooling technologies in the tropics.

Simulation:
The use of an energy modelling tool for this project was to predict the behaviour of the building (at full capacity) and to establish a baseline to compare the ECOPHIT system to a conventional VAV system. Furthermore, the detailed outputs from the BMS can validate the accuracy of the building model. For this project, EnergyPlus was used as the energy modelling and simulation tool which has been tested rigorously, which had already been previously used for similar analysis.
Lighting is estimated to contribute for around 17% of total energy consumption of a building in Singapore. The replacement of traditional lighting systems with LED can, at present, save a large amount of energy (80% for incandescent, 55% for fluorescent). The objective of this project is to save much significant amount of energy for indoor lighting installations in office spaces. The project is being demonstrated at CleanTech One Building, at ERI@N office level 5.

Traditional fluorescent lighting fittings (double T5 40 Watts) are replaced by high lumens LED fittings (22 Watts). These fittings are equipped with sensors (occupancy, temperature and daylight) and DC “Power over Ethernet (PoE)” drivers (LED transformers). PoE is a technology allowing to power and transfer data with a single network cable (RJ45 connection).

Renewable energy partly powers the LED installation; thus, a significant amount of energy can be saved. As PV generates DC power, generated power is first transferred to batteries for storage, and after stabilization, it can be directly used to power LED through PoE.

All LED lights are connected to a lighting management software for control. This system adapts and optimizes light distribution and brightness to occupancy, in order to light spaces only when it is needed.

The installation and its use are metered with DC sub-metering RS485 Modbus RTU interface every 5 minutes. Data are collected and exported for analysis.

The outcomes and next steps for this type of installation will be:
1. Energy saving by retrofitting LED luminaires: ~54%
2. Energy saving by proposed DC grid solution and intelligent control system: ~26%
3. Deployment of WiLLs solution at CleanTech One for ERI@N office
4. Deployment at CleanTech 3 for the entire building
FUTURE MOBILITY SOLUTIONS

Singapore, through the efforts of ministry of transport (MOT), the land transport authority (LTA) and academic institutes, is moving towards a vision of sustainable future mobility. Underpinned by public transport, Singapore aims to be a car-lite city with minimized congestion and pollution, where trips would be supplemented with self-driving vehicles, as well as buses/shuttles for first and last-mile transportation. Seamlessly connected mobility would be further facilitated with intelligent mobility solutions and smart-devices.

To bring Singapore closer to this vision, the Land Transport Authority (LTA) is investing in research, development, test-bedding and deployment capabilities. ERI@N will play a central role in a number of these areas including autonomous vehicles’ certification, AV sensor integration, and electromobility solutions centred around public transport. These technologies would be readily transferrable to megacities around the world which will face serious challenges in road congestion and pollution.

Programme at a glance

<table>
<thead>
<tr>
<th>Established</th>
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</tr>
</thead>
<tbody>
<tr>
<td>TRPs targeted</td>
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<tr>
<td>Research staff</td>
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</tr>
<tr>
<td>Students</td>
<td>PhD:5, Master’s:4, Interns:11</td>
</tr>
<tr>
<td>Participating Professors</td>
<td>Y Wang, A Maswood, J Dauwels, F Klanner, A Iswaran, HW Ng, J Pou, WS Gan,</td>
</tr>
<tr>
<td>Laboratories</td>
<td>Drive train Lab @CTO, BEV Lab @MAE, Test Circuit @ Clean Tech Park</td>
</tr>
</tbody>
</table>

The elements of future mobility (Figure 59) guide the roadmaps of various initiatives for Singapore. While the “informative” and “interactive” elements are related to the nationwide policy matters and IT infrastructure, ERI@N is supporting the government on the technological and regulatory development in the “green mobility” and “assistive mobility” space.

ERI@N Future Mobility Solutions interdisciplinary research programme, together with the local agencies and industry partners, is working towards integrating the following main areas:
- Development of new concepts of Electric Vehicles (EVs) for different fleets of public transport in Singapore
- Development of enabling technologies for deployment of autonomous vehicles (AVs) for first/last mile public transport, ports and logistics industry
- Assessment of energy demand at the distribution power grid, arising from the number of Electric vehicles (EV) & possible solutions
- Road-mapping the deployment of electric vehicles and autonomous transport solutions in Singapore’s fleets by introducing EVs and AVs
- Technology type and charging infrastructure required for different fleets
- Regulations and certifications of EVs and AVs

The FMS group has focused on the following key stages of applied RD&D: component level that involves designing and developing EVs and AVs, fleet level involving test-bedding, and system level that studies and analyses concepts for mass deployment.

Technology development in this programme is inspired by the problems that transport agencies and automotive industries are confronted with. Concepts are developed right from idea level and matured to the extent of field testing of prototypes. This leads to successful intellectual property development and opens up the option of licensing to the industry. The commercialization mechanism happens either through the industry partner or through start-ups.

![Figure 59](source: Land Transport Authority)
The future mobility lab BMW@NTU at ERI@N was established in April 2013 as a joint initiative between NTU and BMW-Munich. The team works on innovating new technologies for advanced driver assistant system and overall traffic management, having already developed a set of advanced driving services for BMW drivers, most of which are being integrated into the company’s vehicles for real product implementation.

The Intelligent Mobility (IM) team under BMW@NTU future mobility lab focuses on routing and parking services modules, as shown on Figure 60. All research projects are in tight cooperation with the industry partner, and will be or have already been integrated into BMW backend server. The projects will provide premium mobility services to BMW drivers as well as fleet managers.

The IM team also pioneers research on the following six projects, namely: traffic breaks down prediction, stochastic routing, cooperative routing, routing for parking, ParkGauge, and parking recommendation.

Traffic incidents prediction aims to provide the drivers with the accurate estimation of the duration of incidents. With the predicted duration at hand, ITS can well inform the driver whether to change the planned route or not. A cluster-specific data-driven method was also developed to predict the duration of traffic breakdowns, accidents etc., which not only predicts the duration, but also provides the associated confidence level. Furthermore, the main objective is to predict the impact of the incidents on the neighbouring upstream links as well as the network as a whole. Based on the historical dataset containing several external features, it is possible to predict the spatio-temporal impact of the incidents on traffic speed.

Stochastic routing problem is crucial for traffic and transportation. It takes into account various uncertainties in real-world traffic and yields route recommendations dynamically, which leads to finding better solutions to the development of sustainable transportation systems. In this project, cases of route planning are considered, in which driver utilities are also governed by deadlines, such as catching up flight, fire rescue and organ delivery, situations that require punctuality with the maximum chance. These critical cases render the LET and mean-risk model-based stochastic shortest path impractical in real applications. Therefore, a probability tail model is proposed to find a path that maximizes the probability of reaching destination before a deadline. Partial Lagrangian and fitted Q-learning methods were proposed as the solutions to the problem, and the projected algorithms have been integrated in BMW routing backend (Qtrip) for beta-test.

The cooperative routing project aims to routing 10% of the total vehicle populations cooperatively, so that the overall traffic jam situation in the megacity can be alleviated, and drivers can benefit in terms of travel time and less waiting time. The FMS team proceeds in model-free reinforcement learning methods for automatic cooperative routing among vehicles. A novel algorithm was implemented in renowned traffic simulator (SUMO, Simulated Urban MObility) by the team. The project has been selected by LTA for field test in the coming year, and by 2019, the project is expected to work in operational mode in Singapore.

The remaining three projects focus on Parking-related services. Drivers in megacities generally spend a lot of time looking for a parking spot. The Routing-for-Parking project uses crowdsensed information to recommend a last-mile driving route, so that the driver has the maximum chance of coming across a free parking lot. The ParkGauge project estimates the total time spent when a driver try to park a car in the Parking Garage. With this information (time spent on parking), offering the driver a more accurate ETA (estimated time of arrival) is achievable. The Parking Recommendation project offers the driver miscellaneous parking related information, such as parking fare and walking distance to the final destination, so that he/she is able to make a well informed decision. The knowledge gained in these projects is used to improve the local services in future.

Future Endeavours
The BMW@NTU future mobility lab is constantly growing. An Autonomous Vehicle research centre is been set up on NTU campus, as well as pioneering mobility services for electric vehicles.
1. Autonomous Mobility-On-Demand solution at NTU campus

Singapore’s limited land space and growing population sees an endless prospect of the economy steering towards the adoption of autonomous technology in every sector. To cater to the projected high volume, high frequency transport requirements in a given space and both by public segment as well as by the logistics industry, it is apparent that existing modes of transport will not be feasible. One way to resolve such rapidly changing mobility system is to introduce varying stages of autonomy in various modes of transport. Ongoing research is continuously and seamlessly introducing driverless vehicles on roads in the form of private cars, taxis and buses. Some compelling use cases have already emerged in industries like logistics, shipyard, theme parks and campuses, as they express broad willingness to adopt autonomous technology.

This project aims to introduce a driverless and self-sustained mode of transport at NTU campus. This test bed is the first of its kind in the region and could pave the way for the integration of autonomous vehicles in Singapore’s transport system, to alleviate the “first mile, last mile” transport problem faced by urban cities.

The project aims to develop an autonomous transportation mode (ATM) for the first and last mile connectivity for people and goods, and provide support to the existing transportation system. The vehicles deployed for use in this system will be fully self-driving with features to interact with other autonomous vehicles, commuters and stations, providing the information about arrival time, traffic conditions and current location. An on-demand, cloud based supervision software has been developed to enable NTU students & staff to remotely book the shuttle service and pinpoint the nearest pickup location.

Many enabling technologies have already been developed. AVs will be equipped with flash charging capabilities via super-capacitors, which will be designed to enable charging the on-board energy storage system in less than 2 minutes. A 1.5kW demo unit has already been developed and tested, which runs with 85% efficiency. A 10kW prototype is currently being developed with 95% DC-to-DC efficiency. The concept of rapid-opportunity-charging will also be implemented, utilizing the unique working profile of urban transportation, which includes fixed routes with short distances between stations, for a smooth mobility and a constant speed profile with few stops.
Project 3: Electromobility - Drive train and energy storage

1. Power train development for range-extender
   The power train of an electric vehicle comprises of an electric motor, a power converter, energy storage system and controllers. A typical drive train platform is being developed in-house, that will be used to experiment with multiple technologies that form an integral part of the EV drive train. Concepts like designs and packaging of components in a vehicle are also being developed in-house. Testing of high power density indigenously designed motors for propulsion is being carried out. These are primarily internal permanent magnet machines or in wheel motors.

   Besides design and testing of components, the drive train will be used to test various drive cycles for the range extender concepts. Combinations of energy storage such as batteries and super-caps or batteries and fuel cell are being tested.

   A test-bench flexible enough to test the effective solutions at component level and interaction of these components at a system level is required. Ongoing projects in this domain are related to machine designs for traction motors, vehicle-to-grid interaction, and energy storage assessment for a given drive cycle.

   Figure 63 gives a snapshot of the design process for a traction motor, the motor was designed and is being tested in the drive train lab.

2. Snap-in Modular energy packs for E-Motorbikes
   Two wheelers, due to their low cost and easy operability in a congested traffic, have traditionally been a very popular mode of transport in China, India and other Associations of Southeast Asian Nations (ASEAN). Although substantial progress has been achieved over the past decades, e-motorcycles are still somewhat hampered by heavy energy storage devices, with limited capacity and relatively slow recharging capabilities. Given these limitations, this project gives emphasis on designing low mass, energy efficient battery packs for rapid charging and hot swapping.

   Global market research estimates strong opportunity for growth in the electric two-wheel vehicle market. Though electric two-wheelers, such as e-motorcycles, offer a competitive solution for quick, cost-efficient and green transportation, they are yet to be improved. Range per charge, short service life, high costs, and lack of charging facilities, in general, are the elements that affect larger up-take of the market.

   As a quick and simple solution to address the initial cost barrier and charging facilities for e-motorcycles, the project proposes a snap-in modular battery system with 50% lesser volume and 30 min charging time. The parallel modules can be charged independently by plugging out the modules from the e-motorcycle. This project involves fabrication of 1.2kWh Li-ion battery module for high energy density, high power and high life as compared to the conventional lead acid battery packs.

   To further strengthen their capability in this field of electric mobility market, they are keen to develop proprietary products for future distribution in their markets. The next steps include a Technology Readiness Level (TRL) 7-8 project, eventually leading to deployment of these bikes in Singapore and South East Asia.

3. Low Carbon Transportation: flash charged trams for NTU campus
   Buses are one of the major emission sources in Singapore. In 2005, the transport sector alone contributed 19% of Singapore’s carbon dioxide emissions. Currently, more than 3500 buses are in service on Singapore roads every day. This number will grow significantly if Singapore’s population expands to the targeted 6 million. This project is a first-of-its-kind in Singapore with an approach to maximise the usage of existing resources as electric vehicles by pushing the charging process. The project is also a solution for prevailing first-mile and last-mile transportation problem. It is an overall innovative mobility approach to address in a holistic way all kinds of individual mobility with a sustainable solution, which can be readily adapted at places such as university/polytechnic campuses, science parks, business districts, tech parks located away from the MRT stations.

   There are several practical challenges in adoption of EVs in Singapore. High cost and weight arise because of the batteries on board and the requirement to replace them. The proposed solution would be to take this energy storage off the vehicle and reduce it to just 1/20th of its current weight. For charging an existing electric vehicle, it has to be stationed at a charging station for 6 to 8 hours, which reduces availability of the vehicles. To overcome this issue, fast charging is proposed as the
solution. It requires substantial modification on the power grid assets to manage the power intake. The proposed solution is to minimize the on-board energy storage to weigh under 100 kg. and to charge it more frequently. For a route with known stops, whether it is for a campus internal shuttle or public transport buses, this solution promises to increase energy efficiency.

In this project, one of the various competing technologies will be designed, developed and demonstrated using a test bed in the campus. The key element in this technology will be a tram with very minimal on-board energy storage and frequent and very fast charging of this energy storage.

The research group of the industry partners and NTU will install 2 charging stations and 3 bus stops between CleanTech Park (CTP) and Research Techno Plaza (RTP). Prototype flash charging stations integrated with renewables and hybrid energy storage powered tram will be tested on the designated route. Successful field tests and charging demonstration will help accomplish the fully functioning electric tram for NTU campus.


Concept of this project will allow a 24/7 fully electric solution for port vehicles. The project involving electric port equipment needs to overcome significant obstacles due to the limited battery life leading to limited travel distance, charging time resulting in restricted mileage per charge, temperature, cycle life, infrastructure, and cost. Electric Port Transportation (EPT) concept utilizes the unique working profile of fixed routes with short distances between stations, relatively low speed and constant working profile with multiple stops, and targets towards a fully electric solution.

The proposed system is a very efficient, scalable and universal energy storage unit that can perform the functions of power conversion, distribution, energy management and storage using intelligent control strategies and minimal components. The universal power distribution and management system (UPDMS) can take multiple hybrid energy packs for traction applications. Its fully featured battery management system (BMS) is compatible with all kinds of battery packs that reduce the customization effort and dependence on a single battery manufacturer. Advanced features such as thermal management, intelligent cell balancing, predictive health monitoring and fault isolation are achieved using proprietary algorithms. Self-commissioning scheme also enables auto detection of battery packs. These features are a result of novel power converter topologies and intelligent control strategies. Therefore, new concepts and methods used in this project will drive future research and be widely applicable in various seaport terminals in Singapore and beyond.

5. High Power Density Energy Storage Solution for Stationary & Mobile Applications

Battery electric vehicles (BEVs) are an attractive alternative to conventional cars due to their zero emissions and lower environmental impact. Research is currently focused on designing and developing alternative battery modules, thermal management of batteries, rapid and flash charging of batteries. This project focuses on the liquid cooling of battery pack. The enclosure is designed to carry the coolant to each individual cell evenly, effectively and efficiently using a novel packaging design. With the novel structure and concept, the liquid cooled battery pack would be compact, lightweight, have large energy capacity and plug-and-play capability for quick swaps at petrol stations. Thermal management can retain the battery capacity above 80% for up to 9 years and liquid cooling can increase the battery’s life span by 2 years compared to air cooling.

The performance of an electric vehicle (EV) depends strongly on the performance of its high-voltage battery pack, which is influenced by temperature. Therefore, focus should be put on the thermal management of batteries in EVs, including cooling and heating issues. An enclosure has been designed which contains structured grid to facilitate a flow path for coolant, i.e. to provide efficient and evenly-distributed cooling for every cell. The challenges addressed are thermal management of battery pack and demonstration of fast charging capability.

The objective to create a simulation model showing thermal characteristics and flow of coolant in the thermal enclosure has been successfully achieved. A battery pack prototype comprising mainly of cells, battery management system, thermal enclosure and pump for circulating the coolant has been set up. Charge and discharge tests at various C rates and a record and analysis of voltages and temperatures while the pack is charging and discharging has also been successfully accomplished.
Project 4: Electromobility roadmap for Singapore

Singapore, like many other developed cities in the world is moving towards deploying clean means of transport. ERI@N has helped the government to lay down the electro-mobility roadmap. Besides supporting the government with regards to policies, technology development has gone hand in hand. This is to ensure that the chosen technology for mass deployment in Singapore is sustainable.

The National Research Foundation (NRF) and the National Climate Change Secretariat (NCCS), together with the relevant government agencies are working together with members of the research community and private sector, to develop a series of technology roadmaps on energy and climate change related technologies.

The Land Transport Authority (LTA) as part of the roadmap development effort intended to deliver the electromobility technology roadmap until the year 2050. ERI@N was instrumental to create the electro-mobility roadmap to provide a blueprint to guide the formulation of policies and infrastructure plans that will enable electro-mobility deployment in Singapore.

The project was structured in five phases as illustrated in Figure 66.

Several scenarios about how the global share of electric drive trains in the overall vehicle population will develop have been published by the International Energy Agency (IEA) and further renowned organizations. As a city-state which finds itself in constant competition with other attractive cities worldwide, Singapore aims at more ambitious targets. Table 1 demonstrates the low, medium and high fleet electrification scenarios for the shares of EVs in Singapore’s fleets by 2050, based on assessments of relevant stakeholders from industry, academia and government.

<table>
<thead>
<tr>
<th>Fleet Electrification</th>
<th>• Electrification between 134,000 EVs (Low scenario) and 532,000 EVs (High Scenario) in 2050 • Public Buses and Taxis inherit the biggest potential for electrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Demand</td>
<td>• The High Scenario requires 6.9% of today’s electricity consumption in 2050 • The High Scenario requires 45% of projected PV electricity generation in 2050</td>
</tr>
<tr>
<td>Emissions and Abatement</td>
<td>• Substituting a conventional bus in Singapore with a battery electric version could lower emissions up to 56% per vehicle already today • EVs can bring emissions 30% down compared to BAU in 2050 • EVs powered with PV can bring emissions 64% (3 Megatons) down compared to BAU in 2050</td>
</tr>
<tr>
<td>Competitive Research</td>
<td>• Strong research landscape • Perfect test-bed Conditions • Competitive advantage potential in • Autonomous urban electric (micro) systems • Smart connected urban electric transport • Charging infrastructure solutions • System integration • Continue research in next generation batteries with strong monitoring of outcomes to justify investment and ensure leading edge research</td>
</tr>
<tr>
<td>Charging infrastructure</td>
<td>• Infrastructure to be built by private sector, in case EV market is accelerated and investment framework provided by politics • Main barriers: policies, regulations and invest uncertainty • Standard recommended: Type 1 and compatible CCS Fast Charging System</td>
</tr>
</tbody>
</table>

Table 1 Technology development roadmap for penetration of clean transport systems in Singapore
Maritime transport service carries around 90% of global merchandise by volume, with fuel consumption of 339 million tonnes annually. Similar to power plants, ships are equipped with large engines to produce power for their propulsion and usage. Heavy fuel oil (HFO) is the predominant source of fuel oil used by ships. Until now, there are more than 50,000 ships with an average engine size of 5.6 MW and three auxiliaries of 750 kW each. These engines run 300 days per year with the 365-day operation of auxiliaries. Under business as usual, the growth rate of ships is estimated to be around 4% or 2,000 new ships per year.

Shipping represents around 60% of global transport SO₂ emissions and around 4-9% of global anthropogenic SO₂ emission. As for NOₓ, it is responsible for around 40% of global freight transport NOₓ emission and for around 15% of global anthropogenic NOₓ emissions. For CO₂, international shipping contributes to an estimated 2.2% of global GHG emission in 2012. With around 70% of ship emission occurring within 400km of coastlines, the International Maritime Organisation (IMO) has taken an active approach to address increasing environmental concerns with regulations aiming at driving technological development (E.g. energy efficiency, emission control & cleaner fuels) to meet future clean shipping.

Programme at a glance

<table>
<thead>
<tr>
<th>Established</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRs targeted</td>
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<tr>
<td>Research staff</td>
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<tr>
<td>PhD students</td>
<td>4 (cumulative) / 2 (current)</td>
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<td>Key Professors</td>
<td>SH Chan, X Wang, J Lam, A Yan, L Hua, A Chakraborty, T Tjahjowidodo, LJ Min, A Romagnoli, A Miserez</td>
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<tr>
<td>Laboratories</td>
<td>Maritime Energy Test Bed (METB), Electro Chemistry Lab @CTO, Energy System Lab @MAE, Centre for Biomimetic Sensor Science @RTP, Laboratory for Clean Energy Research @EEE</td>
</tr>
</tbody>
</table>

In Singapore context, the Singapore Maritime Cluster (SMC) Vision 2025 was recommended by the 3rd Maritime Research and Development Advisory Panel (MRDAP) in 2007 to sustain competitiveness in the maritime sector and attract maritime companies to the city-state on a global level. Several recommendations were suggested to achieve SMC Vision 2025, among them, focus RD&D thrusts in key areas like energy, environment and maritime operations, with more attention on knowledge creation and its use on business development and application in the maritime sector. In 2013, SMI mapped out a national Maritime RD&D Roadmap 2025 to identify strategic RD&D opportunities for Singapore and related stakeholders.

Among several RD&D initiatives is the creation of the Maritime Clean Energy (MCE) Interdisciplinary Research Programme, jointly by the Maritime and Port Authority (MPA) & ERI@N, with the objective of developing a research platform with focus on green energy management solutions for Singapore’s Maritime Industry. MCE taps on the ecosystem of maritime-related research led by the Maritime Institute @ NTU (MI@NTU) set up in partnership with SMI. MCE programme also leverages on the expertise and know-how related to energy efficiency and low-carbon energy generation across various research programmes in ERI@N.

Research areas in MCE programme include green shipping and green ports. Areas under green shipping covers research in alternate energies & clean fuel, carbon capture & emission management, electric propulsion and energy management systems, while in the green ports initiative, it encompasses energy efficiency & electrification, green technologies, cold ironing and port energy management.
Project 1: Exhaust Emission Control - ZEDSMart, Zero-Emission DeSulphurization process for Maritime applications: Novel process and pilot scale demonstration

Shipping accounts for about 9% of the global sulphur emissions and it was estimated that large vessels can potentially contribute to about 5,000 tonnes of SO\(_2\) annually. Due to the projected expansion of maritime industry and the detestable evidence on public health, regulations have been set up to aim at significant reduction of SO\(_2\) in the coming years. This requires the large-scale deployment of scrubbing technologies to remove SO\(_2\) from flue gas. Most existing technologies employ seawater as a scrubbing agent. While this technique has obvious advantages such as the use of low cost scrubbing agent, it has several shortcomings. Firstly, the scrubbed sulphur compounds, usually present as sulphates, are disposed into the sea. These discharges would have long-term ecological consequences and may be regulated in the future. Secondly, the process requires enormous amounts of seawater using water pumps, which can be energy taxing and expensive, and may result in large equipment that will reduce the cargo capacity of the vessel.

ZEDSMart uses a proprietary non-flammable, non-toxic, liquid solvent that is capable of efficient removal of SO\(_2\) in the flue gas. The key novelty of the process is that the SO\(_2\) removed is concentrated and stored on-board for further conversion to valuable products. The solvent used in the process has a higher SO\(_2\) capacity thereby allowing the realisation of smaller equipment and lower pumping costs. Since the process involves a regeneration step, solvent losses are expected to be minimal. It is estimated that the space needed to install the equipment for desulphurisation may be comparable to that of the seawater scrubbing. Furthermore, it offers the possibility of profit making arising from the concentrated SO\(_2\) product.
Project 2: Exhaust Emission Control - Development of a Total Solution of Exhaust Gas Cleaning System and its Installation for Dry Cargo Carriers

In response to global concerns over sulphur oxide (SO\textsubscript{x}) and particulate matters (PM) emissions from ships, the International Maritime Organisation (IMO) has enacted the legislation MARPOL 73/78 Annex VI, which specifies new mandatory standards for phasing in cleaner engine fuels to reduce the emission of SO\textsubscript{x} and PM from the shipping industry. The regulation enforcement will help to reduce a significant amount of SO\textsubscript{x} emissions and, at the same time, the enforcement will impose additional cost on ships inevitably. It is estimated that there will be around 50,000 ships, out of which 21,000 dry cargo carriers will be affected worldwide. It is also estimated that at least additional 240 million tonnes of 0.5%S HFO are required to support shipping industry in 2020 with the refinery investment in the order of USD 100 billion. Every 100 tonnes of 0.5%S HFO produced will generate additional 4 tonnes of CO\textsubscript{2} emission. The cost of 0.5%S HFO is predicted to be 20%-50% higher than that of high sulphur HFO and this results in a higher operational cost for shipping industry. If 0.5%S HFO is not available, ships will need to operate using a distillate fuel (i.e. MDO or MGO) at a significantly higher price. This approach will also result in a glut of HFO in the market.

Within the context of IMO MARPOL Annex VI, alternative “Exhaust Gas Cleaning System” is accepted instead of reducing fuel sulphur contents. By installing EGCS, ships will be able to continue their operations using the current cost-effective HFO.

The proposed project aims to study the significance and impact of using EGCS as an approach to comply with IMO SO\textsubscript{x} emission standard in non-ECA (0.5%S HFO) and to develop a total solution of EGCS, beyond scrubber alone, to expand its availability to dry cargo vessels. It should be noted that dry cargo vessels account for the largest percentage in terms of the total numbers of ships. Dry cargo vessels have limited space, leading to difficulty to install EGCS currently in the market. The total solution of EGCS will facilitate maritime industry to meet current IMO requirement in terms of SO\textsubscript{x} emission reduction in 2020 in an economically viable approach, and will also provide solutions for ship owners to tackle with future challenging regulations foreseen to be enforced (such as new parameters for wash water, CO\textsubscript{2} emission and sludge handling). The development of a total solution of EGCS for this segment will lead to an enormous reduction of SO\textsubscript{x} emissions.

The total solution of EGCS will overcome the difficulty to retrofit the available EGCS to existing vessels and to install to new building vessels, especially to dry cargo carriers and become a genuinely environmentally friendly system, i.e. meeting foreseen new challenging regulations on quality of wash water to be discharged into the sea, appropriate approach for sludge handling or utilisation and compensation to CO\textsubscript{2} emission due to EGCS operation.

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Ships pollute the environment when they burn heavy fuel oil (HFO) or bunker oil to run the generators on board ships. One container ship pollutes as much as 50 million cars do annually. Studies indicate that shipping-related emissions lead to approximately 60,000 cardiopulmonary and lung cancer deaths annually. The use of shore power derived from cleaner fuel helps to eliminate air emissions associated with on-board generators powered by bunker fuel. Shore power represents a cheaper and cleaner alternative to power ships while they dock at berth.

The proposed LEMS would manage energy storage, electrical energy generation, load and electric energy sale/purchase with land-based upstream networks. The prototype not only synchronizes both the shore and vessel grids automatically before closing the circuit breaker between them, but also provides an application that is capable of metering and charging the kWh amount of shore-to-ship energy. LEMS will incorporate renewable energy derived from renewable sources such as PV panels and also traditional energy. The operation will be optimized to enhance the overall efficiency. The proposed prototype helps to switch from the ship's heavy fuel oil (HFO) to cleaner land-based fuels (primary gas) and hence cuts down CO₂ emissions. It opens up new business opportunities for shipyards or ports by providing electrical energy to ships.
Project 4: Technologies for Energy Efficient Marine Vessels - Biomimetic-Based Antifouling Coatings as a Route to Improve Energy Efficiency of Ships and Port Structures

Fouling marine organisms that attach to underwater structures are causing major economic costs to the shipping industry and are increasing its environmental impacts. By settling on ships, organisms such as barnacles and mussels increase hydrodynamic drag, lower the manoeuvrability, and in turn increase the fuel consumption by as much as 40% with additional greenhouse gas production estimated to be 20 million tonnes per annum. Efficient strategies to reduce biofouling are hence critical to increase the energy efficiency of ships. In Singapore, the major fouling organism is the green mussel Perna Viridis, an invasive species which sticks to virtually all underwater structures in very high density. In order to reduce this detrimental effect, development of anti-fouling coatings is key, with pressing needs for eco-friendly remains modest, being mostly based on empirical formulation without a clear understanding of the underlying biofouling mechanisms. Consequently, strategies for coating development must target the specific physico-chemical mechanisms of adhesion. For macro fouling, the key characteristic lies in the adhesive proteins used by organisms to stick to underwater surfaces.

The savings to the shipping industry through the use of antifouling coatings is estimated to be S$40 billion per year. Clearly, there is an urgent need to develop efficient antifouling coatings. This proposal seeks to tackle biofouling – initially of mussels and later of other fouling organisms – onto immersed structures, and to lower their detrimental effect, using the following 3 step methodology: (1) Reveal the adhesion mechanisms of adhesive proteins at the nano-scale; (2) Isolate and sequence unknown adhesive proteins that play a critical role in fouling, and compare their adhesion energy with that of known proteins; (3) Precisely tailor recently-developed coatings from our industrial partner that will be designed to minimize adhesion. Laboratory fouling assays on coated surfaces and nano-scale adhesion force measurements will be employed to optimize novel antifouling coatings. The project will be geared toward the translation of new coatings and design principles to the maritime industry.

Figure 71 Fouling Species in Singapore (L), Laboratory artificial seawater with live mussels (R)
Singapore’s environmental ranking has worsened as published in the latest living planet report by World Wildlife Fund for Nature. Among 150 countries, Singapore has the seventh largest ecological footprint (WWF, 2014). The port industry nowadays is subject to closer scrutiny due to concerns on environmental pollution and resource preservation (Lam and Notteboom, 2014; Yap and Lam, 2013). As a world class hub port, Singapore is expected to demonstrate its capability in sustainability. Therefore, there is a strong demand for developing a new and effective solution to achieve green port operations and enhance the productivity/growth simultaneously.

The concept of this project is based on the state-of-the-art supercapacitor technologies which will allow a 24/7 fully electric solution. The project involving electric port equipment needs to overcome significant obstacles due to the limited battery life leading to limited travel distance, charging time resulting in restricted mileage per charge, temperature, cycle life, infrastructure, and cost. Electric Port Transportation (EPT) concept utilizes the unique working profile of fixed routes with short distances between stations, relatively low speed and constant working profile with multiple stops, and targets towards a fully electric solution.

The proposed system is a very efficient, scalable and universal device that can perform the functions of power conversion, distribution, energy management and storage using intelligent control strategies and minimal components. The universal power distribution and management system (UPDMS) can take the multiple hybrid energy packs for traction applications. Its fully featured battery management system (BMS) is compatible with all kinds of battery packs that reduce the customization effort and dependence on a single battery manufacturer. Advanced features such as thermal management, intelligent cell balancing, predictive health monitoring and fault isolation are achieved using proprietary algorithms. The self-commissioning scheme also enables the auto detection of battery packs. The storage capacity can be upgraded by interconnecting supercapacitor modules that are easily swappable.

These features are a result of novel power converter topologies and intelligent control strategies. Therefore, the new concepts and methods used in this project will drive future research and be widely applicable in various seaport terminals in Singapore and beyond. The research and the knowledge created to contribute to maintaining Singapore’s competitive advantage and its status as a hub port. The project deliverables will also raise the RD&D capability profile of Singapore as a maritime knowledge hub.

Project 5: Electrification of Ports - Smart Cargo Handling Equipment and Battery Management System for Port Sustainable Energy

The concept of this project is based on the state-of-the-art supercapacitor technologies which will allow a 24/7 fully electric solution. The project involving electric port equipment needs to overcome significant obstacles due to the limited battery life leading to limited travel distance, charging time resulting in restricted mileage per charge, temperature, cycle life, infrastructure, and cost. Electric Port Transportation (EPT) concept utilizes the unique working profile of fixed routes with short distances between stations, relatively low speed and constant working profile with multiple stops, and targets towards a fully electric solution.

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The two Flagship Programmes, EcoCampus and Renewable Energy Integration Demonstrator - Singapore (REIDS), are a differentiator for the institute, where a unique eco-system and facilities have been created for plug-and-play experiments in a “Campus Laboratory” for EcoCampus, and on an “Island Laboratory” for REIDS.

Both flagship programmes provide major infrastructure and resources for technology development for the tropical environment and focus on significant outcomes in energy efficiency and renewables respectively.

They aim to:

a) undertake emblematic integrative projects with bold and audacious goals that will achieve significant research outcomes
b) provide a platform for multi-disciplinary research across ERI@N
c) develop and retain long-term competence in systems level research
d) provide an avenue for NTU research projects and for industry partners to develop their innovations at scale in real-world, Living Lab environments
e) create a blueprint to be implemented across different campuses/industries across Singapore and overseas.
Flagship Programmes
These solutions differ significantly from traditional challenging endeavours between two meetings/lectures. Under the EcoCampus programme, the ‘Living-Lab’ principle and engagement of industry partners in the development and commercialisation of technologies. The initiative was launched officially on 30th April 2014, with a mission to achieve an impactful target of a 35% reduction in energy, water and waste intensity on the campus by 2020, while leading the development and adoption of innovative technologies at NTU.

Programme at a glance

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</tr>
<tr>
<td>Laboratories</td>
<td>Living labs: NTU Campus and CleanTech Park</td>
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The EcoCampus Initiative is built on applied research and test-bedding of innovative technologies at the NTU campus and the neighbouring CleanTech Park sites. In this RD&D framework, three themes are integrated synergistically together, viz. research and education, the ‘Living-Lab’ principle and engagement of industry partners in the development and commercialisation of technologies. This programme is set to achieve its objectives by leveraging on the deep technical expertise at NTU and active participation from industry partners. This will balance the academic and scientific aspirations with tangible deployment outcomes for sustainable energy solutions. It will also have a multiplier effect on growth in the energy sector that is based on job creation, productivity, capability building and entrepreneurship development.

The key research drivers for EcoCampus are urban solutions related to energy efficiency and sustainability with a clear niche on solutions for the hot tropical climates such as Singapore. Building technologies such as air-conditioning, mechanical ventilation as well as lighting have been developed mostly in temperate climates, and their application in hot tropical climate require significant adaptation or re-thinking of technology benefits. For example, dehumidification is a key concern for tropical air-conditioning systems and materials used for building envelopes and facades can weather and perform differently in such climate.

NTU has taken a big leap in renewable energy adoption by installing a 5,000 kWp rooftop Solar PV system, which is the largest rooftop PV system on any University campus around the world. Urban mobility concepts developed under the EcoCampus programme focus on solutions that are relevant for people movement on campuses or business parks. The typicality’s here are short distances and need for last-mile connectivity. Framing the problems in this setting calls for innovations such as opportunity based charging of electric vehicles at shorter distances and use of personal mobility solutions that are amenable to the hot tropical weather (e.g. riding bicycles can be challenging endeavour between two meetings/lectures). These solutions differ significantly from traditional electric vehicle development challenges related to long range and charging times. As Singapore moves towards a Smart Nation, there is an increasing need to developed solutions that are connected and can feed real-time information into data analytics engines. The NTU Campus spans across 200 hectares and has more than 150 buildings including academic, commercial, offices, laboratory and residential buildings. Each of the building types has its unique energy profile and with varying occupancy rates (due to school terms), the energy usage patterns are highly variable. This offers various energy management and conservation opportunities that need data-driven analysis and decision making.

With 33,000 students and 7,000 staff on campus, the energy efficiency technologies implemented on the campus would also need to consider the impact on human comfort and behaviour. This is true for any urban setting but often remains a forgotten or under-prioritised area of interest. There are several opportunities to achieve high-level of energy savings through user-engagement and appropriately influencing user behaviour towards energy conservation.
Air-conditioning and mechanical ventilation represents more than 60% of the energy consumption of a typical commercial building in Singapore. Most commercial air-conditioning systems use a central chiller plant and air-handling units to supply cooling for air-conditioned spaces. The central chiller plant (with electrically driven compression chillers) determines the primary energy used for cooling and often accounts for more than 35% of the total electrical load of a building. With the various laboratories, offices, lecture rooms and commercial spaces on the campus, the seven chiller plants on the NTU campus account for about 15% of total campus energy consumption.

This project studies impact of a novel control optimization strategy to improve the performance of a central cooling plant which provides cooling energy for a mini-cluster of academic buildings on the NTU campus. The goal of this study was to identify the operating range of every component to minimize the overall chiller plant power consumption for a given cooling load, weather and building conditions. In most cases, including this case study, the chiller plants usually do not operate at this optimal range. This concept of an ‘intelligent, demand-based chiller optimisation’ platform has to certain extent being commercialised by an industry Partner as its demand flow technology, mainly in the United States. The RD&D project was carried out at the N3.1 chiller plant on campus, which serves four different buildings on the campus with a total average peak cooling load of 900 tons.

The project implementation involved installation of variable frequency drives for the pumps (condenser water and chilled water pumps) and cooling tower fans. Additional sensors and power meters were also installed where required, along with the demand flow control and data logging system. In the initial few months after installation, the system was commissioned and fine-tuned for its operation in the local context with the help of data analysis (weather data, load data and system data such as temperature, differential pressure and flow). This also helped to set the optimisation boundaries and the sensitivity of variables for the optimisation algorithm. The setup was installed in a way that it was easy to switch from the baseline mode (no dynamic controls) to the Demand Flow control mode in order to collect performance data for comparison.

After the operational fine-tuning, performance data from the chiller plant was collected over a period of comparable load conditions (between March to May 2016). From the data analysis, it was found that the control system is able to achieve a 12-15% improvement in the chiller operational efficiency through the optimisation programme. Figure 74 shows the system performance data. Further fine-tuning of the optimisation algorithm is in progress to explore the highest saving potential without compromising the operational effectiveness. It is expected that up to 30% chiller efficiency improvements can be achieved, especially at lower part-load chiller operations.

Project 1: Intelligent, Demand-Based, Algorithmic Chiller Optimization for Buildings in the Tropics

Figure 73 Photo of the N3.1 chiller plant room implementation

Figure 74 Comparison on performance of chiller plant after Demand Flow (DF) control implementation
Data centres, that house and maintain the back-end information and communication technology (ICT) systems, represent a large chunk of energy footprint of many buildings in our cities. Currently, data centres contribute an estimated 3.5% of total electricity bill at NTU. With increasing emphasis on ICT in modern universities, it can be anticipated that a higher share of energy consumption by the university will be borne by data centres. Modern ICT equipment such as high performance servers used in data centres requires much higher heat release per unit volume making development of new cooling technologies a necessity for future applications. In Singapore’s high temperatures and very humid tropical climate, provision of adequate and efficient cooling for data centres is challenging and currently represents about 50% of their energy cost, according to National Environment Agency (NEA). Therefore, it is important to look into pioneering energy efficient data centre cooling technologies for tropical climates in order to achieve future campus sustainability, and to be in the forefront of high energy efficiency technologies.

A previous RD&D project was conducted by ERI@N in 2011-2012 to assess the potential of outdoor air-cooling in modular data centres with Toshiba as the industry partner. The current RD&D project is proposed to push the limits on data centre cooling efficiency further by using the Liquid Immersion Cooling technology.

Based on lab-scale experimentation, it is expected that the liquid immersion cooling system will reduce the overall energy consumption of the data centre by more than 30%. The resulting Power Utilisation Efficiency (PUE) of the data centre is expected to be less than 1.2, which is a significant reduction over typical tropical data centre PUE of 1.8-2.0. The overall space utilisation for data centres can also be drastically improved as the liquid immersion cooling compacts the space that is otherwise used for the air-conditioning equipment such as chillers, air-handlers and air ducts.

The objective of this project is to demonstrate a liquid immersion cooling system to provide energy efficient cooling for data centres in tropical climates. This liquid immersion cooling system test bed will be the first-of-its-kind in Singapore. The technology has been developed by 3M company initially, up to near-commercialization stage and this project is expected to fill the important gaps between RD&D and full-scale commercialization. The scale-up from the lab experiment involves several RD&D challenges such as follows:

- Selection of suitable liquid for the two-phase immersion cooling concept (considering the boiling point, environmental impact, conductivity properties, corrosion potential, etc.)
- Design of the tank for immersion cooling to optimize the thermodynamically considerations, while ensuring practicalities such as maintenance access and space utilization
- Dehumidification and moisture handling considering our tropical conditions
- Improvement of boiling conditions with suitable boiling enhancement coatings on the server components and tank design
- Design of the vapour loop and heat-rejection unit to minimize the energy requirement, thus improving the efficiency.

The test bed will be carried out at the High-Performance Computing Cluster (HPCC) on the campus with 20kW of servers used as central computing resources in the data centre. At this stage, the system design has been completed and installation is on-going. The system performance will be measured and reported once fully commissioned.
Project 3: Demand Control Ventilation for Energy Reduction in Laboratories

It has been identified that laboratories, internationally, use five to ten times the amount of energy when compared to office buildings due to the unique operation and energy demands. Conventionally, laboratories are operated using 100% outdoor air (OA) and at high air change rates (ranging from 8-12 air changes per hour (ACH), and as much as 15-25 ACH) for ventilation. One study indicates that the cooling and ventilation energy consumption at the Laboratory for the National Institute of Health in Maryland, USA is 22% and 44% of the total building energy demand, respectively. Singapore also has the unique challenge of the hot humid climate where greater energy is required for dehumidification of the air.

A Demand Control Ventilation (DCV) or (Demand-controlled Ventilation) system adjusts outside ventilation air based on the number of occupants, processes involved and the ventilation demands for the space. Aircuity Inc. from the United States has developed a multiplexed sensing technique to draw air-samples from the laboratory space and analyse the air quality using gas chromatography at a central location. The real-time data from the analysis is then used to control the ventilation rate of the air instead of relying on a fixed value for the ACH. Centralized demand control ventilation for critical spaces is new to Singapore and NTU. With this demonstration, the research team will be able to understand and experience this technology first hand, its benefits in the long run, incorporating demand control ventilation into their serving organization.

The site chosen for this study is the highest energy consuming academic facility on campus, viz. the School of Physical and Mathematical Science (SPMS). A 1,165 m² physical lab space in the chemistry building was selected as one of the demonstration areas due to the high potential for energy savings, being a representative for other laboratory spaces at SPMS and NTU. A 1,335 m² area within the common facilities block was selected as a meaningful demonstration site, as it will represent energy saving potential lecture halls, tutorial rooms and meeting rooms. As of now, the DCV installation has been completed and the sensors are already gathering the air quality data. However, the system is not connected yet to the Building Management System (BMS) that will facilitate the control actions to reduce the lab ventilation rates. Hence performance data from the installation is not yet available.

One of the main challenges in implementation of this technology in laboratories is that it should be installed and operated without compromising the health and safety aspects of the laboratory. Hence, NTU has led the setup of a voluntary working group of laboratory experts in Singapore to assess the risks associated with laboratory ventilation rates and develop guidelines towards selecting a suitable lab ventilation rate. This group is known as the Risk Assessment Ventilation Optimisation Group (RAVOG) and has members from NTU, National University of Singapore (NUS), A-Star and private laboratory consultants and practitioners. The group also keeps folks from the University of California, Irvine and the International Institute of Sustainable Laboratories (I2SL) from the United States on its advisory panel.

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Project 4: An Interactive solution to Improve the Energy Efficiency using User Behaviour and Gamification

User engagement and behaviour should be one of the critical elements of energy conservation strategy. Often times, low cost or zero cost solutions to reduce the energy intensity can be found by purposefully engaging the user and influencing their behaviour towards energy conservation. There are several published studies in the literature proving that increasing user awareness and engagement can result in positive energy conservation behaviour and direct energy savings of between 10-40%.

The main research problem in designing an effective user engagement tool is the user appeal and efficient engagement of users in the call-for-action. The solution to this problem can be understood in modern behaviour science and sociological studies, plus the fact that the smartphones is the dearest and nearest communication device, directing us to use this platform for effective communication of energy conservation and sustainability related messages.

Based on this background, the ERI@N research team, along with industry partner Engie, embarked on developing a first-ever smartphone app pilot for interactive user engagement using the sociological concept of gamification. The PowerZ app, as an experimental app to foster people in energy efficiency improvements, includes game elements (game story, achievements, avatar, levels/points, etc.) but is not a game per se. The project uses game elements to make the pedagogic and engagement experience more entertaining and engaging. The PowerZ app design has been produced with a constant progress loop between Engie Lab Singapore and the researchers at NTU including two professors from the school of Humanities and Social Sciences. The game design has also been completed and enriched through the involvement of the Earthlink NTU student society community members who got involved in PowerZ experimentation at all stages.

The PowerZ app facilitates a two-way communication between the users and the building facility managers. The main features of the app are two interactive elements:

- A Cold/Hot feature: This feature enables the PowerZ users to interact with the NTU energy facility management about their temperature feeling in the NTU Campus classrooms.
- Eco Gestures: The EcoGestures are small daily actions that the PowerZ have to perform to reach the PowerZ achievements (flowers design, points, lucky draw challenges, etc.).

Both these features are gamified in the app in form of points system, enabling a social scoring system that can show the top player on the game leader board. E.g. to earn points, the users have to unlock the 17 Eco Gesture cards, learn about the eco gestures actions and energy impacts, and declare their actions on a daily basis.

For four months, the PowerZ app project gathered more than 1,850 students (namely 4.4% of the NTU population) during four months of experimentation between February 2015 and June 2015. The app also registered a large number of activities as follows: 13,500+ Hot/Cold declaration; 53,000+ EcoGestures; more than 300 daily users actively using the application.

A sociological study using a student survey and quiz was done after the first experimental phase of PowerZ from mid-February until mid-June 2015. The main purpose of the sociological study and data analytics was to determine the impact of PowerZ among the students of NTU. The analysis is based on quantitative and qualitative methods. The study suggests that the use of the app increases the awareness about energy consumption and fosters eco-friendly behaviour.

Outcomes
As an RD&D Program, the following outcomes or Key Performance Indicators (KPIs) are set forth for EcoCampus initiative by year 2020:

- 35% Reduction in energy, water and waste consumption intensity
- 20 New Industry collaboration projects
- 5 new IP creation
- 2 spin-off companies
- Green Mark Platinum Award for the whole Campus
- Greenest Campus in the world: International recognition

The test-bedding phase of the initiative has provided a good platform for identifying and finalising technologies that can help to achieve the impactful 35% resource reduction target.
Access to reliable, safe and affordable energy is one of the key challenges humanity must address and resolve during the 21st century. While diesel generators do contribute to local pollution, their operational costs, primarily due to long and expensive fuel supply and transportation operations, are generally far beyond the means of the populations they aim to serve.

The major issue is that of overall cost before environmental impact. The overarching focus of REIDS is on the integration of selected renewable energy technologies with suitable energy storage systems to serve the needs of isolated villages and islands, and less so on the development of these individual technologies themselves which is the focus of highly qualified RD&D centers in Singapore and the region.

Research and development are needed to develop breakthrough technologies as well as to advance the understanding of interdisciplinary systemic interactions taking not only engineering, but also economics, environmental impacts, societal reactions and political realities into consideration.

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<td>Laboratories</td>
<td>Semakau Landfill, Power Electronics @ ERI@N, Fischer Tropsch Pilot @ SCBE</td>
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The REIDS technology roadmap, illustrated in Figure 80, is built on a Technology-Systems tripod: (a) renewable energy sources, (b) energy storage systems and (c) integration by way of microgrids under the control of intelligent and adaptive energy management systems.

Diesel generators often provide for the majority of the energy supply, however sporadic, for islands and isolated villages. Entirely replacing them in the context of enhanced local energy supply is not realistic. The strategy championed by REIDS is integrating the existing diesel gen-sets within a local microgrid infrastructure, such that they simply become one among several electricity sources. As more renewable energy production is integrated, the diesel fuel consumption will gradually decrease to eventually reach a situation where the diesel gen-sets’ primary role is that of back-up and no longer that of predominant energy source. For entirely “green field” installations, diesel gen-sets might still have to be installed as back-ups for critical loads; careful technical-economic studies will need to take place to find the suitable balance between long-term energy storage usage and diesel gen-sets.

Once the microgrid infrastructure is in place and as the local energy requirements evolve, renewable energy sources and storage “modules” are to be added using a “plug and play” approach which is essential to ensure sustainable deployment costs in remote locations.

Proactive participation of both private and public entities is vital toward the long term success of REIDS. Complementing the Technology-Systems beforementioned, REIDS is built on the partnership tripod of: (a) equipment manufacturers, system integrators, utilities, energy services providers and consultants, (b) public funding agencies, public policy entities and regulators, and (c) finance sector.

As a result, REIDS is conceived as a consortium of large and small corporations from the region, East Asia, the United States and Europe, along with Singapore public agencies.
Project 1: Offshore REIDS: Tidal Energy Environmental Impact Assessment of Southern Islands of Singapore (EIA)

Ocean energy systems form a viable clean energy source to support remote coastal and island regional energy needs. Deploying ocean energy systems can revamp the regional growth and people lifestyle. However, such ocean energy deployment is of concern to environmentalists and government agencies to ensure least interference to other marine industries and individuals.

Presently, an environmental impact assessment (EIA) study is being carried out, investigating the baseline conditions, possible effects of the test sites on the surroundings, and other associated research. Geotechnical and geophysical surveys are also being planned. The objective of the study is to analyse four sites of Singapore southern islands (Seringat, Tekkukor, Semakau and St. Johns) and to identify the best site towards setting up a scaled test site for further evaluation of tidal turbine systems to suit the tropical resource conditions of South East Asia.

This study is unique in its investigation towards systematic investigation of environmental impact assessment of tropical waters and provides an environmental management framework imperative in the feasibility study to ascertain the deployment of ocean energy systems and their impacts on ecological and aquaculture receptors, water quality, seabed geology, underwater acoustics and hydrodynamics on adjacent ocean industries such as fish farm, maritime, reclamation, defence, telecommunication, recreation and tourism.

Testing sites play a crucial role in fostering the development of the industry. While several high energy potential locations associated with strong tidal currents in Europe, North America and North Asia have long been identified and harnessed, the tropical markets for lower-tidal-velocity distributed generation, for instance in South East Asia, are yet to be explored. As there is no full scale or even scale test site available yet in the South East Asian region, it is challenging to test and develop tidal turbines towards this regional need. This study helps to investigate the southern islands of Singapore to set up a scaled test site, Tropical Marine Energy Centre (TMEC), to invite the turbine developers to test their technology in tropical conditions, and to commercialize it in collaboration with ERI@N to promote more ocean renewables into the regional energy mix of South East Asia.

The project aims to deliver:
- A detailed design of tropical floating tidal test system to characterize different tidal turbine and evaluate its performance characteristics and reliability before it is confirmed by the industrial partner for its system suitability for the rest of South East Asian water conditions.
- A systematic environmental impact assessment guideline from the present project experience to practice in upcoming full scale tidal turbine deployment sites of South East Asia to achieve minimal impact of other marine users such as shipping, defense, fisheries, tourism, ferry transport etc.

The present progress includes a 5m rotor tidal turbine system (50 KW) with four-point mooring system under Singapore tidal, wave and wind conditions as shown in the Figure 81. The surge, sway, heave, roll, pitch and yaw characteristics have been evaluated using a detailed hydrodynamics study based on the field measurements. Detailed tidal and wave energy resource assessment of southern Singapore has been obtained by utilizing field measurement of tidal flow and seabed morphology and computational fluid dynamics.

The project focuses in the following basic research:
- To identify the right sensor systems and perform signal analysis to characterize the tidal current and incorporate into a hydrodynamics study.
- To characterize the seabed morphology through an acoustic Doppler sensing system.
- To study the relation of underwater acoustics from tidal turbine system and their interaction with seabed and coastal system and to understand the attenuation characteristics.
- To study the wake level characteristics interference of the floating barge system with the rotating tidal turbine to minimize structural loads.
- To study the interaction of wake level feature and turbidity and its influence on the seabed morphology and coral reef structures to minimize possible environmental interference.

Project investigation methodology
- After systematic tidal resource measurement, soil seabed studies, water quality studies, benthic studies, meteorological and oceanographic studies are performed.
- Perform detailed barge level hydrodynamics studies by incorporating field level measurements of tidal flow conditions, seabed morphology, mooring design details, barge material, design conditions, etc.

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Figure 81 Numerical model prediction of tidal resource condition of Singapore Waters
Project 2: Multi-microgrid Implementation

From a test and demonstration viewpoint, the overarching purposes of the REIDS microgrid system are:

• To demonstrate how microgrids can operate in an isolated, off-grid mode using several Renewable Energy (REN) sources coupled with selected Energy Storage Systems (ESS), under the monitoring and controls of specially developed Energy Management Systems (EMS) to serve a range of various load types as can be found on isolated islands and villages in South East Asia.

• To demonstrate how microgrids can operate between them, microgrid interoperability, using specially developed coordination EMS.

• To demonstrate how isolated or multi-microgrids can operate connected to a local electric distribution network by way of an intermittent tie-line.

In addition, each microgrid serves as hardware test bed for the development of innovative technologies, subsystems, as well as for the development of innovative monitoring and control software platforms. Finally, the REIDS microgrid system serves as a “show case” for the REIDS industrial and institutional partners. As a result, flexibility of new component installation and operation is the key consideration driving the design of the REIDS microgrid system further described below.

The design for three almost identical microgrids is being finalized. Each microgrid will feature PV and wind energy production facilities as well as dedicated energy storage systems. Each microgrid will be capable of operating fully isolated under the supervision and control of dedicated energy management systems, EMS. One of the EMS will be the one developed under the PMM project described earlier.

The electrical distribution within each of the three microgrids will be 400 VAC, 3 Ø, 50 Hz. Provisions are included in the design to also accommodate DC distribution to demonstrate hybrid operations of microgrids. The single-line diagram for each microgrid is shown in Figure 82.

Microgrid interoperability will be demonstrated by way of the Link Bus system which will be operated at 6.6 kV, as it will be most likely used to connect microgrids located and operated on separate islands and/or villages. Several assets such as wind turbines and energy storage systems will be installed such way that they can be shared between microgrids – these connections will be done at 6.6 kV or at 400 V.

Once fully implemented, by the end of 2017, the REIDS Multi-microgrid system will provide a fully flexible and adaptable development, test and demonstration platform where new technologies, as well as innovative monitor and control systems can be readily implemented and operated.

Implementation progress
Top soil: Early 2016, NEA completed the task of adding a 2m layer of top-soil over the P2 plot – this represents some 130,000 m³ of soil transported from mainland Singapore were dispersed and compacted. This ensures that the P2 plot is at the same level as the bund surrounding the landfill.

Lease agreement: As of April 2016, NTU entered into a three-year lease with the Singapore Land Authority, SLA, for the P2 plot. The lease started May 1, 2016 and is renewable for another two periods which would bring it to at least 2025.

Soil investigation: A soil investigation project was completed in August 2016 with the purpose of gaining a thorough understanding on the strata and physical properties of P2 plot soil. A total of 26 boreholes laid in grid format were drilled to achieve a full profiling of the plot. The result of the project is important in determining the foundations requirements for the various systems to be installed.

Lead consultant: A Lead Consultant has been hired to support the P2 plot implementation project planning, design & implementation, communication as well as to ensure that the works to be carried out are in accordance with the relevant statutory requirements applicable in Singapore.

SIEW 2016: Important announcements are expected during the 2016 edition of the Singapore International Energy Week, SIEW, October 24 – 28, in general, and during the opening plenary session of the Asia Clean Energy Summit, ACES, October 25.
Project 3: Outreach to South East Asia - REIDS+

Today, 120 million people in South East Asia do not have proper access to electricity; around 106 million in Indonesia, the Philippines and Myanmar alone. Taking Indonesia as an example: the 16,000 islands in the country are in need of better access to electricity, 90% of Indonesia’s provinces are suffering from only intermittent, sporadic electricity supply, while some 8.5 million households are not electrified at all. In the east of Indonesia, one week long blackouts are quite common, as it is walking to a charging station for mobile phone access for a couple of hours.

The situation is similar in the Philippines with its 7,000 islands and with over 70% of its population living in rural areas. Myanmar’s electrification challenges are equally daunting, but in the context of isolated landlocked villages.

In a first step, REIDS+ focuses on Indonesia, the Philippines and Myanmar which are the countries with the highest total numbers of people with no proper access to electricity.

The wide renewable energy and microgrid deployment opportunities in South East Asia provide the main impetus for the REIDS members to cooperate with NTU and ERI@N.

Significance and Scope

Investment decisions have to be based on a clear understanding and knowledge of the local market conditions and developments. In order to support REIDS members in their business development activities, the REIDS+ initiative seeks to:

- Broadly disseminate the REIDS activities in South East Asia through conference participations.
- Raising awareness and educate through seminars and workshops throughout the region.
- Gather, develop and structure country specific market information to be shared with members.

During the first three quarters of 2016, REIDS programme was presented at the Power & Electricity World Asia 2016 conference in Jakarta, the ASEAN Sustainable Energy Week in Bangkok, the Renewable Energy Project Financing Forum 2016 in Kuala Lumpur, and the Myanmar Green Energy Summit in Yangon. Specific Conference Summaries are prepared and shared with members after each event participation.
Two distinct markets, but related by way of the technologies required to address them, are of primary interest to the REIDS members:

- Islands and isolated villages suffering from an inadequate or fully unavailable electric energy supply.
- Deluxe resorts where the primary source of energy are diesel generators. The present trend toward “eco-tourism” clearly requires the reduction on environmental impact by these resorts.

It is not the purpose of entering into systematic support and even less so the deployment of microgrids. However, proactive participation in pilot projects with REIDS members are essential to validate the results emanating from the REIDS’ RD&D projects and also, when needed, to adjust the RD&D orientations.

1. Pilot projects in the Philippines – two island communities

Collaborations with utilities in the Philippines with potential applications to:

- San Jose DPP, an island of 22 km² with a population of about 11,000 inhabitants in 5 barangays.
- Maripipi DPP, 28 km² island with a population of some 7,000 inhabitants in 15 barangays.

In both cases, the issue is the need to increase the average daily electricity availability from 12 hours to 16 hours per day. It is hoped that deploying and integrating renewable energies and suitable energy storage will be less costly, considering investments and operating combined, than simply adding more diesel generators.

2. Pilot project in Indonesia – deluxe resort

The reids team is working with island resorts in south east asia to investigate the possibilities of significantly decreasing, and eventually fully curtailing the use of diesel generators. The resorts, have a high focus on sustainability presently barges in all diesel fuel and all cooking gas required for its operations and switching to renewable and microgrids would present a very significant opportunity in cost savings, reliability of electricity supply, and also sustainable development.

In addition to renewable energy deployment, mechanization of wet and dry waste is envisioned as well as longer term energy storage technologies such as hydrogen, for example.
ERI@N ACCELERATOR PROGRAMME

The full economic benefits of any research are extensive, sometimes difficult to quantify, and not always well understood. Universities are hotbed of innovative research and technology and play an important role not only in fostering innovation and entrepreneurial growth, but in stimulating recovery in regional and global economies as well. It is imperative therefore, that the focus is not solely on core education and research environment but to translate to entrepreneurship and company formation too, in order to contribute in job creation and making economic impact.

To this end, ERI@N has started to embark on initiatives to bringing technologies to the market place.
ERI@N Accelerator Programme
The full economic benefits of any research are extensive, sometimes difficult to quantify, and not always well understood. Universities are hotbed of cutting edge research and technology, and play an important role not only in fostering innovation and entrepreneurial growth, but in stimulating recovery in regional and global economies as well. It is imperative, therefore, that the focus is not solely on core education and research environment, but to translate to entrepreneurship and company formation too, in order to contribute in job creation and making economic impact. To this end, ERI@N has started to embark on initiatives to bringing technologies to the market place.

ERI@N is strategically placed in the wider domain of clean energy and energy efficiency, focusing on applied research and deployment with targeted industry participation, providing the opportunity to understand problems, and work accordingly on relevant solutions that are practical, deployable, cost effective, scalable and marketable.

The institute understands that, for an organization to be successful in breeding innovation, its working model should not be much different from a typical start-up that comprises agility, flexibility and quick decision making. It is therefore, beginning with an accelerator environment where technologies with identified market-need applications are assessed, on its merit of novelty, scalability, industry impact, sustainable model, and market size. ERI@N starts supporting inventors from the very early stage of developing a product or service, up to proof of concept or proof of value stages. This helps to de-risk the project by accelerating development at an early stage, so a quick decision could be made to continue forward, pivot or to put the project on hold on the basis of outcome.

The aims of the ERI@N Accelerator Program are:

1. Accelerate the transition from lab to commercialization for technologies aligned with ERI@N’s core vision and mission
2. Provide facilities, seed funding, mentorship for staff and students to take their inventions or inventions from around the world to the market place
3. Support the development an entrepreneurial and innovation culture across NTU and Singapore.

With the help of accelerator model, the targeted solutions for relevant industries could range from a Technology Readiness Level (TRL) of 3-9, of which the lower TRL (3-6) activities of applied research can be undertaken by ERI@N, with the start-up addressing the higher levels (7-9) which are typically more commercial in nature.

To date, there are about 12 start-ups which have spun out of ERI@N. The focus ranges from materials, energy storage, internet-of-things, software as a service, power electronics, air-condition and mechanical ventilation, amongst others. Some of these start-ups are presented on the next page.
Start-ups

Advanced Air T & D Systems

Air T&D was spun off from ERI@N and School of Electrical and Electronic Engineering (EEE) in March 2014 and majorly focuses on research, development, and eventually manufacturing of components, appliances and systems for indoor air conditioning and ventilation. The ultimate objective of Air T & D is to act like a catalyst to build more energy efficient MVAC components, manufacture advanced products and splendid services in the domain of air treatment and distribution technologies, concentrated to create value for all stakeholders of the domain, such as communities, customers and investors.

Two of the advanced products developed by Air T & D are “Terminal Units –Active Thermosiphon Beams (ATB) and Passive Thermosiphon Beams (PTB). These terminal units are more energy optimized based on four major physical phenomena such as air entrainment effect at the nozzles, air thermosiphon effects, displacement ventilation for heat exchange process, and coanda effect. Additionally, ATB technology is a breakthrough in avoiding condensation.

Amperics Singapore Pte Ltd

Amperics Singapore Pte Ltd is a joint venture company formed between NTU and Amperics Inc, a company based in California, USA. Amperics Inc has developed proprietary technology for the manufacture of high performance super capacitors based on surface redox phenomena. Amperics Singapore leverages the IP developed by Amperics Inc, by using Singapore engineering talents, collaborating with ERI@N and licensing of additional IP from NTU to complement Amperics Inc’s own IP. Amperics Singapore will not only further product development but also eventually serve as a manufacturing and marketing arm for Far East operations.

Amperics has identified two industries that have a strong need for advantages provided by its technology: mobile phone markets and light vehicles. Increasing the energy available to mobile phones will have a notable impact on customer satisfaction and an increase in device single charge life time. Singapore’s constantly connected population will surely benefit from the effects of this increased capacity. Amperics is part of the ecosystem required to improve the feasibility of electric vehicles, and will do so by providing increased storage capacity of power sources.

The proprietary technology relates to the construction of an asymmetric supercapacitor employing a composite electrode with titanium dioxide, activated carbon and carbon nanotubes. The particle size on TiO2, in addition to the ratios of each material in the composite, is very important to obtaining high energy and power densities. The ratios of material have already been optimized and demonstrated in flooded cells and coin cells, which are standard lab scale cell configurations used to validate technology performance. The next important step of development would be to build a supercapacitor that will meet the specifications of a real product (e.g. cell phones), and integrate the prototype into said product to demonstrate a functional system supported by our technology. The following are the upcoming milestones targeted by the company: integration of all the device components, development of suitable lightweight packaging, prototype development and characterization of prototype, and testing in mobile phones followed by light electric vehicles.

Amperics plans to align itself with a supercapacitor manufacturing firm. In conjunction to it, it would develop its own customers and also benefit from customer relationships via the partner manufacturing firm. Through this strategy, faster means of market engagement would take place, thereby building the Amperics name quicker in the market. As the business develops, the proportion of individual product revenue streams will change reflective of the different applications being pursued.
CommSens

CommSens is a spin-off company from ERI@N focusing on smart energy management using Internet of Things (IoT) technology for environment sensing, sensor fusion and data analytics. The main differentiator or CommSens will be the deployment of low-cost, wireless and non-intrusive sensor networks with appropriate low-power communication technology to collect data from any space quickly and in real-time. The data can be used for ad-hoc, real-time monitoring or systemic data analytics using either local or cloud-based monitoring and analytics services.

The focus is on indoor environment sensing. Although there are hard-wired sensors to collect indoor environment data in many buildings, these sensors often have data that is directly fed to the Building Management System (BMS) and it is practically inaccessible for other purposes. Also, there is a limitation on sensor placement in the indoor spaces such as office and meeting rooms, and more often than less, sensors are placed in the wrong locations. The deployment of wireless but addressable IoT enabled sensors facilitates much comprehensive and accessible sensing of the indoor environment. The sensors currently used are able to monitor indoor environmental parameters such as temperature, humidity, pressure and light levels. In future, further sensors could be ‘fused in’ to the wireless sensor network such as air quality (particulate count, CO₂ levels) and occupancy sensing.

Along with a demonstration project at ERI@N office in CleanTech One, there is a deployment case outside the campus being actively developed for such wireless sensor networks. The use of low-cost wireless sensors would provide a much more productive and efficient alternative for this industry segment.

The future development of technology applications would be towards developing a low-cost IoT enabled Building Management System (BMS) that can be used at several locations where as full-fledged traditional BMS system is not practical. Improvement on sensor fusion and network capabilities with interoperable communication technologies is also in progress.

EnergieWise

“EnergieWise” was established to provide smart and modular energy solutions for industrial applications. Additionally, it aims to address typical challenges of energy storage and energy conversion domain such as life of energy storage solutions, advanced charging options and high cost of such systems. Through extensive RD&D efforts, “EnergieWise” has been able to offer a customized energy storage solution that is capable to extend life of energy storage system up-to 70%, moreover, it reduces the total cost of ownership and enhances the possibility to use clean energy for both stationary and mobile applications.

Another customized solution that “EnergieWise” offers is Electric Vehicle (EV) for industrial applications (e.g. forklifts, trucks etc.) and implementation of advanced charging systems in the industry premises. It reduces higher costs associated with frequent battery replacement of industrial electric vehicles and allows EVs to operate round-the-clock without breaks for charging.

A wide range of customized energy storage and energy conversion solutions for industrial applications gives “EnergieWise” a competitive edge over other solution providers. The unique features of such solutions are as below:

- Customized: Solutions are tailor made for heavy duty industrial usage. These systems possess high reliability and need little to zero maintenance.
- Modular: Provided systems are plug and play and can be interchanged and added to other systems to have greater functionality.
- Scalable: System capacity can be easily increased or decreased depending on type of application.

The company is presently developing three pilot projects for prominent industry group in Singapore.

<table>
<thead>
<tr>
<th>Features</th>
<th>EnergieWise</th>
<th>BYD</th>
<th>eBaracus</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Life</td>
<td>4X</td>
<td>1.2X</td>
<td>1X</td>
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<tr>
<td>Reduction in weight and volume</td>
<td>&gt; 50%</td>
<td>NIL</td>
<td>NIL</td>
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<tr>
<td>Operating energy efficiency</td>
<td>95%</td>
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<td>25%</td>
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<tr>
<td>Dedicated Charging Time (Hrs)</td>
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<td>Hot swap</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Liquid Cooling</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Smart Integration algorithms</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Seamless switching</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Fault Tolerant, plug n play hybrid energy system</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Inbuilt reconfiguration capability and adaptability to application</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2 Plug and Play Energy Storage Solution of “EnergieWise” benchmarked against other existing solutions
Graphene Power Pte. Ltd. was incorporated in June 2012, and spun off from the ERI@N to address the need for advanced graphene based materials for industrial applications in the renewable energy, optical electronics, functional composite materials.

Some of our achievements are:

- Received $5M funding globally, mainly from China Energine
- Own international IPs, US2014087192A1, WO2013130018 A1, TD/317/14
- World leading technology on graphene conductive, protective coating

KVI Pte Ltd

The company holds exclusive, worldwide IPR based on Thermodynamics technology (ETM) with application to batteries, fuel cells and electrochemical capacitors addressing academic and industry sectors. The advantage of using electrochemical thermodynamic data, such as enthalpy and entropy, is that they are much more sensitive indicator of small changes in battery electrode state than other types of conventional electrical and physical spectrometry measurements. ETM applications include battery states assessments, including state of charge, state of health and state of safety. The company was incorporated with four products in mind – battery scanner, smart chip, smart battery charger and charge gauge.

Currently, the battery scanner BA-2000 has been developed. With Singapore’s government funding, it is being upgraded and further enhanced with more features. The remaining 3 products are being conceptualized and will be rolled out in due time.
Energy Research Institute @ NTU - ERI@N

**Printed Power**

**Key Inventors**
- Prof. Subodh Mhaisalkar
- Prof. Madhavi Srinivasan

**Major Funding Source**
- Dyesol, SPRING Singapore, National Research Foundation (NRF)

"Printed Power" was established to address the need for self-powered electronic devices, e.g. Wireless Sensor Networks (WSN), and typical challenges of need for frequent battery change, high cost of ownership and lack of end-to-end solutions. WSNs are widely used in smart cities, smart urban solution, smart buildings, smart healthcare and many more, by connecting the physical world object to the internet, and giving meaningful insights to consumers. Majority of WSNs are battery powered or draw power from the building electric grid. The real power of being wireless can only be unleashed when these systems are plug-n-play and could provide seamless, reliable integration, and perpetual source of power. "Printed Power" has developed an energy harvesting power management module which is capable of scavenging freely available unused energy around the electronic device to charge itself.

To demonstrate the harvesting capability, the team has also built a low power wireless sensor network which can measure temperature & humidity at regular intervals. The wireless sensor network is powered with energy harvesting power management unit. The sensor stores data on a local gateway/server, which can be visualized in graphical or 3D animation format.

It is significant to mention that “Printed Power” has completed its first deployment at DB Schenker Warehouse, Singapore: A WSN that can monitor temperature and humidity. Lately, the spin-off was able to raise a significant funding from NRF under the Technology Incubation Scheme.

**OceanPixel**

**Key Inventors**
- Dr. Michael Lochinvar S. Abundo

**Major Funding Source**
- Industry and Institute Associations

OceanPixel Pte Ltd (OP) was incorporated in September 2014 to address the need for knowledge creation in the offshore, ocean and marine renewable energy domain. By strategically collaborating with subject experts from the UK (e.g. Aquatera, ITPower) and relevant thought leaders in the South East Asia (SEA), OceanPixel has positioned itself to be the pioneer company dedicated to ocean renewable energy planning and development in SEA region and beyond.

OP has developed an Intelligent Web-based Integrated Geographic Information System & Assessment Tool for Offshore Renewable Energy (ORE) that enables ORE stakeholders to access reliable data sets with multi-site, multi-device, and multi-criteria (with scoring) features that do not currently exist in the industry. This information system and assessment tool also contains regional data sets that have been collated in one portal for easier and faster access for users in order to reach their required data sets (MetOcean analytics, design parameters, site characteristics, device performance in the water, geographical constraints, techno-economic analysis, and even socio-political climate).

Offering technical services, data and report products, OP has various global involvements and currently handles projects in Singapore, Indonesia, and in the Philippines with potential projects in other parts of Asia under development.
"Salus Nanotechnologies" is an advance material spin-off of ERI@N, created with the objective to develop materials that are helpful to make cotton based textiles to become odour and stain resistant, and water repellent. Additionally, the product made of such materials is aimed to help in fast drying of textiles and provides better comfort and hygiene to the users.

An advanced oxidation technology and surface plasmonic effect is used to achieve high performance antimicrobial effect. These active materials are proprietary and have been developed through three years of extensive research and development. The developed products are targeted for daily use clothing to be worn by people in tropical climate like in Singapore. The products have applications in industrial surfaces too for increasing energy efficiency and facilitating easy maintenance.

"Salus Nanotechnologies" is presently working to introduce a novel binding chemistry which makes the technology easy to adopt in textile and other industries. The major potential applications of the product therefore lie in healthcare apparel, elderly-care apparel, sports wears, specialty clothing, commuters clothing, health exchangers, pumps, cooling systems and air conditioning systems

"Salus Nanotechnologies" is funded under National Research Foundation (NRF) under the Technology Incubation Scheme.

SMT Energy Asia Pte Ltd

SMT Energy Asia Pte Ltd (SMT) is a scientific company specialized in the development of coating for a variety of industry fields such as photovoltaic, anti thermal, anti-static, anti reflective etc. They are supported by a strong technical research team comprising of polymer chemists, design engineers, marine biologists, horticulturists and material scientists from ERI@N and School of Materials Science and Engineering at NTU.

SMT's main expertise is in the exploitation of nano materials technology for extensive coating applications and we have developed strong technical know-how and IP competencies in anti-thermal properties for various applications ranging from building and construction, to agriculture and aquaculture industry.

SMT will initially focus on the design and development of clear anti thermal coating. The company will also work with other companies in other anti-thermal fields, such as paint for building, when the opportunity presents itself.

The value proposition to our customers includes the following:
- A highly experienced and interdisciplinary research team which has worked with the Fortune 500 US companies in the field of coating and nanoparticles for various applications
- A pipeline of products for agriculture, aquaculture and paint, for which extensive trials testing is currently being undertaken.
Ultracharge

Key Inventors: Chen Xiaodong, Tang Yuxin

Major Funding Source: Industry for this spin-off at this moment

Smartphones and portable electronics have reached a level of ubiquity which has seen them integrated into every social and commercial interaction. They owe most of this success to the lithium-ion batteries powering them (*Source Nature - Outlooks, 2015, 526, S93). Ultracharge battery technology presents significant game-changing advantages to the entire battery industry that will bring economic and ecological benefits to future renewable energy resources.

Naturally found in a spherical shape, a method was developed to turn titanium dioxide particles into tiny nanotubes that are a thousand times thinner than the diameter of a human hair. This nanostructure is what helps to speed up the chemical reactions taking place in the new battery, allowing for superfast charging. The fast charging technologies will be demonstrated through integration into their current commercial lithium-ion batteries utilising lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) using ERI@N’s prototyping facilities.

Figure 94 shows results from proof-of-principle studies:

a) image of the nanotube gels prepared by our technology and conventional method and SEM images of the as synthesized ultralong TiO2 nanotubes;

b) long term cycling performances at high current density of 25 C up to 10,000 cycles, 25 C referring to charging time in 2.4 min;

c) performance comparison of ultralong TiO2 materials with graphite, Li4Ti5O12 and conventional TiO2 materials, 1 C referring to charging time in 1h, 10 C refers to charging time in 6 min.

Vortec

Key Inventors: Choo Fook Hoong

Major Funding Source: Multidisciplinary Team Project Fund – NTUitive

Vortec is a spin-off specialized in dual flow vortex technology for homes, commercial and industrial buildings. The end product of this technology is an innovative bladeless ceiling fan.

The key features of this fan is the ‘bladeless’ design coupled with vortex, drawing air from the ground level towards the center of the fan, compressing it, and discharging it downwards in a spiral design like a tornado. This creates a twister like airflow that provides a gentle cooling breeze within its envelope as reflected by the computational fluid dynamic (CFD) simulation below.

This novel dual-flow vortex based ventilation is an innovative design that addresses some of the constraints of the traditional ceiling fan. This potentially disruptive technology would solve the low ceiling constraint of our urban homes, being highly energy efficient, 60% more efficient than existing ceiling fan. It can also be positioned on the ceiling or closer to the recipient for enhanced cooling. Additionally, VPL’s fan allows for a light source to be integrated into the fan to create both an up-light and down-light without any shadow effect.

This bladeless ceiling is an ideal match with passive cooling technology that will help to reduce Singapore’s carbon foot-print from air-conditioning by 30-50%.

Two prototypes have been fabricated. Vortec is seeking funding to complete the industrial design and design for manufacturability before going into full scale manufacturing and launching new products. Vortec is currently talking to a number of companies who are interested in licensing the technology.
Cutting-edge facilities that enable ERI@N to pursue excellence in research development & demonstration have been set up within the institute and jointly with the NTU Colleges, such as AC/DC Hybrid Grids, Nanostructured Photo-Systems, Energy Storage & Fuel Cells, Air-conditioning and Indoor Air Quality, Simulation & Modelling, Future Mobility, and Maritime Energy Test Bed.

ERI@N has also established joint research labs with Rolls-Royce (Electrical Power and Control Systems), Johnson Matthey (Materials – Batteries, Energy & Catalysis), Vestas (Grid integration), BMW (Batteries, Electric Drive) and Surbana Jurong (Smart Cities).
Solar Facilities

Research facilities are housed in a Class 100k clean room with a floor area of 400 m². The clean rooms are equipped with multifunctional glovebox systems (2, 4, 7, and 8 ports) with integrated thermal evaporators, spin coaters, and solar simulators for preparation of novel multifunctional perovskites, formation of functional films through spin coating, as well as fabrication and testing of photovoltaic devices in completely inert atmospheres, in order to understand key aspects that affect their optoelectronic behaviour. Large area processing tools such as screen printers, slot-die coaters, automatic sprayers, as well as doctor blade and Meyer rod printing are also available.

To appreciate the impact of fabrication on the material’s properties, bespoke photovoltaic materials and devices are characterised using a wide range of characterisation tools, such as solar simulators, IPCE, various electrochemical instruments (potentiostat and galvanostat), Hall measurements, multiple probe stations. In addition to this, X-ray diffraction, BET surface analysis, surface profiler, FE-SEM (with EDX), atomic force microscopy, absorbance, photoluminescence and Raman spectroscopy are also available.

Other thin film processing equipment includes: atomic layer deposition (plasma and thermal), vacuum- and E-beam evaporators, chemical vapour deposition, single-wafer spin processors, two-zone furnaces, and sputtering tools.
Wind & Marine Facilities

3D printing
The computer aided designs are presently being evolved into prototypes using rapid prototyping systems. To achieve this, a state-of-the-art 3D printing methods for composites as well as metals and metal alloys are used. Advanced instruments such as SLM 280 HL and 500 HL in conjunction with SC3DP (Singapore’s centre for 3D printing) are used for metal and metal alloys’ coupon and component level printing.

Composites manufacturing setup
With the addition of new 3.2m length autoclave (operating at 15 bar pressure and 400 °C), scaled wind and tidal turbines of less than 3m of length can be manufactured, with fibre volume fractions greater than 60%. The manufacturing time can be reduced significantly with the help of elevated pressure and temperature curing, for which a typically out-of-autoclave process would require > 15 hours for curing.

Wind and water tunnel facility
The 3D printed aerofoil sections and blade prototypes are further tested in wind tunnel and water tunnel systems and towing tank facilities. The wind tunnel helps to test the speed range of wind speed mimicking 10 m/sec, and also providing access to large sections with wind velocity ranging up to 90 m/sec, with a turbulence level of around 0.1%. The water tunnel helps the study of aerofoil and hydrofoils in water velocity of up to 0.6 m/sec with a turbulence level of above.

Tidal turbine test bed facility
A tidal turbine test bed was launched by the W&M team in Singapore. The current test bed benefits from amplified flow due to the narrowed channel between bridge piers, which provides manmade flow convergence.

Wind turbine test facility
The W&M programme has developed a wind turbine test site at south of TUAS in Singapore, for testing and deploying of turbines of less than 15m of height, and evaluating scaled turbine along with micro-grid integration. This test bed centre can cater for deploying/testing multiple rotor configurations of up to 6m diameter wind turbines.

Materials’ characterization and testing facility:
1. Mechanical testing is carried out on materials both at coupon and component levels. It is equipped with two fatigue testing machines: axial and rotating bending.
2. FZG gear test rig simulates the accelerated scuffing in the test gear samples. This machine operates at a constant speed of 1450 rpm for a fixed period (21700 revolutions, i.e. approximately 15 min) by successive increasing of loads until the failure criteria is reached.
3. The facility is equipped with advanced characterization instruments for pre and failure analysis of materials using, as listed below:
   a) JEOL JSM–7600F state-of-the-art thermal field emission scanning electron microscope
   b) Bruker D8 Advance X-ray diffractometer with an accuracy of ± 0.005°
   c) Alpha-step IQ stylus-based surface profiler
   d) Quantachrome NOVA 3200 BET surface area and pore size analyser and
   e) Asylum research MFP3D atomic force microscope (AFM).
Energy Storage Facilities

Lab @ School of Material Science and Engineering (MSE)
Facilities at MSE are equipped with wet labs and fume hoods (~100 sqm), and are geared toward supporting synthesis strategies and development of high performance electrodes based on multifunctional nanoscale materials. Fundamental materials characterisation (SEM, TEM, XRD) is also performed on site at the FACTS lab. Batteries and supercapacitors are made in coin cell (2032) and pouch cell format and electrochemical characterisation is performed on a Solartron 1260 Analyser.

Lab @ Research Techno Plaza (RTP)
The RTP labs house both capabilities for development of energy storage devices and solar cells, primarily catering to the latter. The focus is on electrode slurry preparation, electrode coating (doctor blading/screen printing), device assembly (Li-ion batteries/supercapacitors), and electrical characterisation.

Prototyping Lab @ CleanTech One (CTO)
A dedicated Energy Storage Prototyping Lab has been outfitted at CTO. This lab aims to scale-up lab scale innovations, attracting both industry and academic partners that are interested in developing battery technologies in larger formats. It provides a link between typical research lab sized battery testing incorporating low volumes of active material, such as coin cells and those more commonly found in a commercial/industrial setting, such as pouch, prismatic and cylindrical (18650) cells. The lab will address challenges of reliability, scale-up of current technologies and provide a platform to produce prototype batteries utilising new material technologies developed in-house at ERI@N and further afield.

The prototyping lab has a state-of-the-art 40m² dry room facility, (~40 °C dew point with 2 people working inside and dehumidifying capacity of 209 g/h), completed in October 2013. It can provide necessary space for battery fabrication and packaging. Prototype line facilities include dry room and all process equipment from slurry preparation, coating/pressing, cutting/tabbing, to battery assembly & packaging, and testing for making prototype pouch and cylindrical cells. The focus on utilization of prototyping facilities can be categorised into four areas:

- Process Optimisation and Standardisation
- Scale-up
- Prototype Fabrication
- Industry Partnership and Collaboration

Fuel Cells Facilities

Prototyping laboratory @ CTO
The prototyping laboratory @CTO is set up to translate the lower technology readiness level (TRL) research projects to prototypes that can be used to demonstrate the applications to the industry. This laboratory is also a ‘creation workshop’ that we co-develop with our partners to fabricate and demonstrate prototypes for various applications.

Fuel cell laboratory @ School of Mechanical and Aerospace Engineering
The fuel cell laboratory at MAE has a mixture of research activities ranging from fundamental studies to system demonstration in polymer electrolyte membrane fuel cell, solid oxide fuel cell and hydrogen related technologies. This laboratory has the facilities to synthesize materials for characterisation and perform light machining work.

Fischer-Tropsch laboratory @ School of Chemical and Biomedical Engineering
The Fischer-Tropsch laboratory is a new laboratory, set up with funding from the university and designated as one of the strategic research facilities. This is to create the RD&D infrastructure within ERI@N, positioning NTU as a leader in the emerging power-to-power and power-to-gas energy path. The research outcome will be translated to the facilities on Semakau Island, under the Renewable Energies Integrated Demonstrator – Singapore (REIDS) Flagship Programme.

The facilities in the laboratory support the investigation and study of the activity, selectivity and stability of catalysts (both in-house developed and commercial products) for the synthesis reaction. At these facilities, it is also possible to separate, identify and quantify hydrogen, carbon monoxide, carbon dioxide and various forms of hydrocarbons (C1 to C15) with high accuracy and repeatability.
A world class Power Electronics and Smart Grids / Micro Grids laboratory facility has been set up in CleanTech One building. The multi-disciplinary applied research team focuses on the research and development of state-of-the-art power electronic converters/inverters for the integration of distributed energy resources in hybrid AC/DC microgrid to improve energy efficiency, save cost of energy and increase power system stability and resilience.

Major facilities available in the laboratory are:
- RT-Lab Real-Time OPAL Simulator
- High performance oscilloscopes
- DSPACE
- Solar photovoltaic systems of different technologies
- Data acquisition and controllers
- Programmable AC/DC power supplies and electronic loads

Labs available at the School of Electrical and Electronic Engineering (EEE) and the School of Mechanical and Aerospace Engineering (MAE) would also be used for the MESG Interdisciplinary Research Programme purposes. For waste heat recovery projects, the Maritime Energy Test-bed (METB) lab will also be shared with MESG team, particularly the diesel engine to be used for field-testing.

As part of the Smart Multi-Energy Systems project launched in April 2016, the CleanTech 3 building (under construction) will be set up as a 2 MW AC/DC hybrid grid and CleanTech 3 will also have a 1 MW gas engine coupled to a double effect absorption chiller, a 2000 ton-hour (RTH) chilled water storage, a 300kW/300kWh battery storage and multi-energy management system that will be added to it.

ACMV laboratory @ School of Electrical and Electronic Engineering
The Air-Conditioning & Mechanical Ventilation (ACMV) laboratory has a mixture of research activities ranging from fundamental studies to applied research. It will help to optimize energy consumption of conventional components as well as to innovate new products and solutions for tropical climate, which includes:
- Cooling tower energy and water consumption
- Chiller plant systems
- Air distribution system, and
- Filters, to maintain good indoor air quality (IAQ)

Building-modelling and Simulation Lab @ CTO
This simulation lab is located at CleanTech One building, with the purpose of creating a state of the art lab specialized in building modelling and simulations. The objective and vision of the simulation lab are as follow:
- To create a central data base for our existing/future research projects for easier accessibility
- To showcase our capabilities and expertise on building modelling and simulation
- To educate and share modelling and simulation knowledge amongst internal NTU staff
- To perform research, development & deployment of new simulation tools to fill the gap of existing ones, simplifying the simulation process
- To foster collaboration with external parties for advance building modelling and simulation

Technologies available are: 5 sets of high performance computers, an AR (Augmented Reality) and a VR (Virtual Reality) systems have been set up in this lab to address above mentioned objectives and vision.
Future Mobility Solutions Facilities

Power Train Test Lab for Electric Vehicles
This test lab serves as a platform to build and test rapid prototypes. Characterization and configuration of multiple combinations of energy storage systems can be performed, along with the implementation of effective energy management strategies for electric vehicles. Power trains can be tested for real drive cycles in conjunction with experiments on fast charging, regenerative braking and V2G concepts. This Lab is planned to be extended in early 2017.

The Power Train Test Lab aims to provide a platform for design and validation of Autonomous Vehicle (AV) robotics kits. Supervisory controls for the vehicle operation are implemented in simulation environment. Real road conditions are emulated with the help of generators as loads.

The test bench is scalable for a diverse range of applications (50-500kW). The drive trains of buses or electric boats will be tested and validated. This test bench offers an integrated solution for component sizing, performance and system control tuning. Analysis and testing of autonomous vehicle operations, together with a vehicle simulator can be performed.

The test facility for autonomous vehicles is being designed and will be built at the CleanTech Park. This test track, on one hand, will help to validate the designs of various AV types like for first/last mile transport and public transport. It will also serve as the only platform to certify AVs for various applications through carefully selected test cycles and simulations.

Maritime Clean Energy Facilities

Energy Research Institute at NTU (ERI@N) together with Maritime Institute @ NTU (MI@NTU), with support from Singapore Maritime Institute (SMI) jointly set up a Maritime Energy Test Bed (METB) in November 2015 to support RD&D activities for Singapore Maritime industry over the next ten years. The METB consists of a marine engine (1.25 MWe), a resistive load (1.25 MW) and facility for testing of exhaust gas cleaning system (1200 Nm3/hour). The test bed is suitable for RD&D projects relating to energy and emissions, which include alternative fuels, fuel additives, exhaust gas cleaning & emissions monitoring, waste heat recovery and energy storage. The test bed will be a significant component for scientists and researchers to translate their innovative technologies from lab to field applications.

Maritime Clean Energy group also taps on the facilities of NTU, such as Laboratory for Clean Energy Research (LaCER), Centre for Biomimetic Sensor Science in NTU campus, also Hybrid Power Lab, Electro Chemistry Lab and Electrical Drives Lab in CleanTech One.
The EcoCampus initiative uses the NTU campus and the neighbouring CleanTech Park as ‘living laboratories’ for RD&D. The NTU Yunnan Garden campus spans across 200 hectares and has more than 150 buildings. Apart from academic (lecture theatres, laboratories) and office buildings, residential buildings, dormitories and commercial outlets add to the diversity of building typologies on campus. With 12,000 students and 600 staff living on campus, it can be considered a mini-city with a total population of about 40,000 people. The overall campus energy consumption is about 200 million kWh of electricity, which is the only form of energy used on the campus. This electricity is largely drawn from the Singapore grid and the recent installation of 5,000 kWp of solar PV generation would contribute to about 3-5% of the total electricity consumed. As true for most tropical climate buildings, over 50% of the energy used on campus goes to air-conditioning, which is provided by 7 mini-district cooling plants consisting mainly of the chiller and chilled water distribution network that serves one or more buildings.

The CleanTech Park is a 50 hectares’ site located next to the NTU Campus and is Singapore’s first eco-business park developed by JTC Corporation, a national public-sector land developer. With a plan to house up to 15 buildings, it has currently set up two buildings that support the operations of CleanTech companies and research entities such as DHI, Toray, NTU, NUS, A-Star, Diamond Energy, Renesola, etc. As a new development, the CleanTech Park is expected to be at the forefront of test-bedding, offering spaces for early adoption of technology and solutions. ERI@N has been involved in the design of the CleanTech Two building, which achieves the highest rating for green building certification in Singapore (viz. GreenMark Platinum) and, at the same time, incorporates the latest technology innovations such as the liquid desiccant-based cooling system with solar thermal heat. The CleanTech Park actively solicits test-bedding opportunities with a view to implement the technologies and solutions at other JTC sites throughout Singapore. NTU campus and CleanTech Park are part of the Jurong Innovation District (JID), a brownfield site to develop a cutting-edge and futuristic industrial park.

Semakau Island is situated south of the Singapore main island, and it is primarily used as a landfill for the slag and ashes from four waste incineration plants on the main island. In preparation for the construction of the landfill, using brought-in soil, two islands were merged, after which a large “bund” was built to contain the slag and ashes which are collected at one common point, at Tuas, from where they are barged to the Semakau Island landfill and subsequently dispersed.

The REIDS implementation of the research, demonstration and test bed on Semakau Island is articulated around two distinct areas on the island:
- Microgrid 0, implemented on the NEA Transfer Station
- Microgrids 1, 2 and 3 on the 64’400 m2 P2 plot

REIDS benefits from collaborations with several other entities, among them:
- Power Electronics Lab @ ERIAN - CleanTech One
- Pilot Scale Fisher-Tropsch Demonstrator @ SCBE
- Solar Energy Research Institute of Singapore, SERIS
- Distributed Electric Systems Laboratory, EPFL, Switzerland
The Rolls-Royce@NTU Corporate Lab was launched in July 2013, with a joint investment from NTU, Rolls-Royce and NRF. The Rolls-Royce@NTU Corporate Lab was the first to be supported under NRF’s newly launched Corp Lab scheme, and ERI@N coordinated the entire process from preparing the proposals to launching the laboratory.

The lab is arranged in 3 programmes - Electrical Power and Control Systems, Manufacturing and Repair Technologies and Computational Engineering. The Corporate Lab is currently hosting 80 full time researchers and 61 PhD students. Given the size of the lab, it operates independently, with ERI@N providing administrative support. The mid-term review was recently concluded, and discussion on Phase II (to start in 2018) have commenced.

The joint BMW@NTU Future Mobility Research Lab was established in April 2013 with a focus on Advanced Materials for Batteries, Human Machine Interface and Mobility concepts.

Since its inception, new research topics of smart materials and electromobility were added in September 2014 and June 2015 respectively. BMW has also made available the fully electric i3, and plug-in hybrid i8 vehicles to conduct research on real-life driver behaviour and collect in-depth data on vehicle performance. The joint lab has now grown to include 32 research staff and the next phase of this lab will commence in 2018 with autonomous vehicles and mobility services being a significant area of focus.
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Wind & Marine


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RIM / MESG


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SELECTED PUBLICATIONS


MCE


FMS


Here there are some interesting facts about ERI@N since its establishment, in 2010.
ERI@N numbers since its establishment

211 STAFF
From 26 countries

GRADUATED / HOSTED
- 69 PhD Students
- 68 MSc Students
- 100 Bachelor thesis per year
- 96 NTU interns
- 74 Overseas interns

999 Papers Published
78 Patents filled
12 Startups

10% achieved waste reduction on NTU campus until 2015.
EcoCampus' mission is to achieve 35% waste reduction by 2020.

7 Interdisciplinary Research Programmes
2 Flagship Programmes

ERI@N & CLEANTECH TWO
ERI@N was involved in the design of CleanTech Two, achieving a high energy performance of the building by designing "cool coatings", "chilled ceiling" and outdoor-air cooled data centers.

NRF / Create Partnerships
5
Industry Partnerships
32
Professors
153
Graduate Students
300
Patents filled
78
CREDITS

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